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# Long Path Laser Ozone Monitor Evaluation

Michigan Univ., Ann Arbor

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Environmental Sciences Research Lab.
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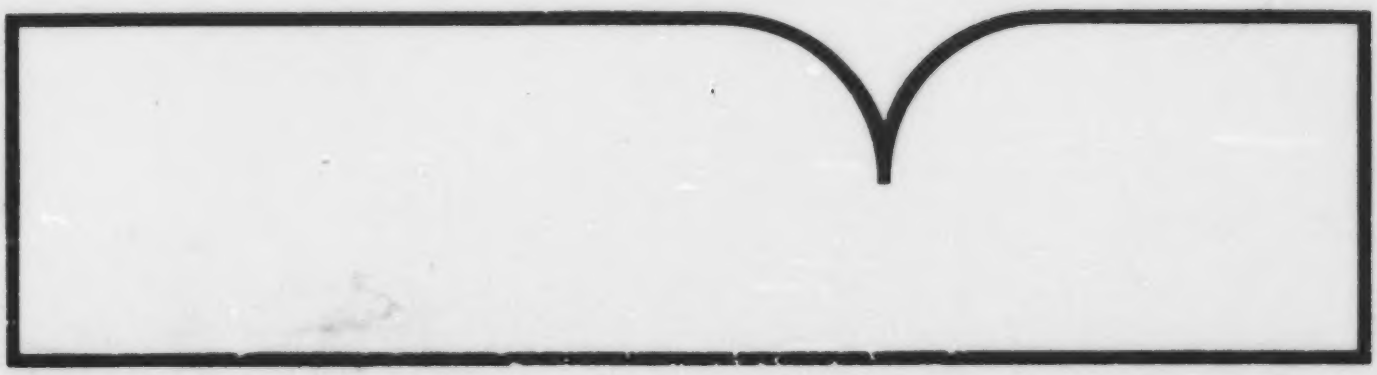

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# LONG PATH LASER OZONE MONITOR EVALUATION

by

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The purpose of the study reported here was to evaluate a long path laser air pollution monitor developed for the U.S. Environmental Protection Agency (EPA) by the General Electric (GE) Company. The monitor was known as ILAMS (Infrared Laser Atmospheric Monitoring System) and designed explicitly for measuring the ambient ozone concentration. The evaluation program was conducted in both the laboratory and under field conditions. In addition to the evaluation several system modifications were carried out; such as, the addition of a beam steering system, the addition of a He-Ne laser alignment system, and various improvements in laser alignment techniques. The field study portion of the evaluation was carried out as a part of the North-East Oxidant Study (NEROS) and was conducted during the month of August 1979. The problem areas identified during the field test were the corner cube reflectors and the irregularity in the laser beam cross-section. The retro-reflectors returned six separate lobes all of which were displaced from the optical center line to form a wave front approximating a toroid. The irregularity in the beam cross-section was previously identified by G.E. However, it was assumed that the irregularities were a function of frequency and closely spaced frequencies would correlate. This assumption does not appear to be valid. The experiments conducted, the modifications made, and the problems identified are completely described in the report.

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## PREFACE

The Environmental Protection Agency has sponsored the development of long path, open air monitoring techniques as part of its research program. With respect to gaseous air pollutants, these techniques have unique advantages in special monitoring situations (1). One of the results of the research was a system called the ILAMS (Infrared Laser Atmospheric Monitoring System). The ILAMS was designed and fabricated by the General Electric Electronics Laboratory in Syracuse, N.Y. It was based on the interpretation of absorption at four infrared wavelengths sent to and returned from a remotely placed retro-reflector. In the current version of the system, the wavelengths were chosen to coincide with absorption features of ozone (2, 3, 4). Initial applications of the ILAMS included field test comparisons with a moving point monitor (5) and field trials in the St. Louis Regional Air Pollution Study (RAPS). Based on the initial field trials, a new system was designed and fabricated by G. E. Several new features were incorporated including a PDP 11/05 for signal sorting and processing, a coated and wedged beam splitter, pyroelectric detectors, and an improved laser power supply. The new system was demonstrated in October, 1978 and the conclusion was reached that there was a system zero drift of unknown origin which would require a detailed analysis. The system was transferred to the University of Michigan for further study and evaluation. The system was subsequently used in the North East Regional Oxidant Study (NEROS) in August, 1979.

The information presented in this report concerns that part of the ILAMS history occurring during and after the new system demonstration in October, 1978.

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## ABSTRACT

The purpose of the study reported here was to evaluate a long path laser air pollution monitor developed for the U.S. Environmental Protection Agency (EPA) by the General Electric (GE) Company. The monitor was known as ILAMS (Infrared Laser Atmospheric Monitoring System) and designed explicitly for measuring the ambient ozone concentration.

The evaluation program was conducted in both the laboratory and under field conditions. In addition to the evaluations several system modifications were carried out; such as, the addition of a beam steering system, the addition of a He-Ne laser alignment system, and various improvements in laser alignment techniques.

The field study portion of the evaluation was carried out as a part of the North-East Oxidant Study (NEROS) and was conducted during the month of August 1979. The problem areas identified during the field test were the corner cube reflectors and the irregularity in the laser beam cross-section. The retro-reflectors returned six separate lobes all of which were displaced from the optical center line to form a wave front approximating a toroid. The irregularity in the beam cross-section was previously identified by G.E. However, it was assumed that the irregularities were a function of frequency and closely spaced frequencies would correlate. This assumption does not appear to be valid.

The experiments conducted, the modificaitons made, and the problems identified are completely described in the report.

This report was submitted in fulfillment of Grant R80665001 by the University of Michigan under sponsorship of the U.S. Environmental Protection Agency. This report covers a period from Dec. 1, 1978 to Sept. 30, 1980 and work was completed as of May 1, 1981.

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## LIST OF ABBREVIATIONS AND SYMBOLS

### ABBREVIATIONS

| | |
|---|---|
| AID | -- Analytical Instrument Development, Inc. |
| EPA | -- U. S. Environmental Protection Agency |
| GE | -- General Electric Company |
| GMC | -- General Motors Corporation |
| ILAMS | -- Infrared Laser Atmospheric Monitoring System |
| NERC | -- National Environmental Research Center |
| NEROS | -- North East Regional Oxidant Study |
| NSI | -- Northrop Services, Inc. |
| ppb | -- parts per billion |
| ppm | -- parts per million |
| RAPS | -- Regional Air Pollution Study |
| RTP | -- Research Triangle Park |
| U of M | -- University of Michigan |

### SYMBOLS

| | |
|---|---|
| $CO_2$ | -- Carbon Dioxide |
| He-Ne | -- Helium-Neon |
| KRS-5 | -- Thallium Bromide - Iodide |
| $\lambda$ | -- wave length |
| $\mu$ | -- micron |

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## ACKNOWLEDGEMENTS

The cooperation of the General Electric Company is gratefully acknowledged and in particular the help of Mr. L. R. Snowman who conducted the original training session on the system and answered many subsequent inquiries. Thanks are also extended to Mr. W. S. Beaman who installed the system at the University of Michigan and answered many questions.

The field test program required the cooperation of many people, in particular Mr. C. Bruce Baker, a graduate student at the University of Michigan, who participated in all phases of the University portion of the program and whose energy and dedication throughout the field study was very much appreciated.

Several Northrop Services, Inc. personnel participated both in the field study and in the system transfer to EPA which was very helpful. Our special thanks go to Dr. George Russwurm who made the retro-reflector photographs and contributed to our understanding of the sytem by his helpful discussions.

The authors thank Dr. W. A. McClenny for his many suggestions and review of this report prior to the final preparation.

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# SECTION 1

## INTRODUCTION

The grant effort at the University of Michigan initially consisted of a program to evaluate and redesign the ILAMS to eliminate problems encountered in the acceptance tests of Oct. 1978. The grant was later expanded to include the use of the ILAMS to obtain vertical ozone profiles as part of an EPA summer field study, the North East Regional Oxidant Study, designed to examine the fate and transport of various air pollutants.

The NEROS application required a long path system capable of measuring over a kilometer distance with a retro-reflector to return radiation to the source location, the type of measurement situation envisioned for the ILAMS. The decision to commit the ILAMS in the NEROS was made after the zero drift problem was identified and eliminated. Additional field performance tests were planned prior to NEROS use and supplemental funds for the field study were provided. The preparations for the NEROS, the NEROS testing and the eventual transfer of equipment to the EPA at the Research Triangle Park, N.C. concluded the grant activities.

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## SECTION 2

## CONCLUSIONS

The conclusions for the grant can be grouped into four categories: (1) redesign of the ILAMS; (2) controlled testing results; (3) NEROS results; (4) final system status.

Redesign: A crucial factor in the ILAMS operation is the maintainance of a stable relationship (ratio) of power returned from the remotely placed reflector, $I_s$, to the output from the $CO_2$ laser, $I_r$, under short pathlength conditions (no ozone or atmospheric burden). Using a short pathlength configuration, the drift in $I_s/I_r$ for the wavelengths was reduced by an order of magnitude by removing the windows covering the pyroelectric detectors and thereby eliminating temperature dependent Fabry-Perot interference effects.

Controlled Testing: The ILAMS was successfully modified to locate distant targets in a vertical plane by installing an Aerotech ARS 304 Elevation Drive. Additional modifications were incorporated which permitted a He-Ne laser to be used for all optical alignments, i.e. for aligning optical components in the system and for sighting in on the remotely placed retro-reflectors. Prior to testing in the NEROS the ILAMS was tested along a 210 m path at the University of Michigan. The path was defined by the $CO_2$ laser source mounted in a sheltered area and a retro-reflector placed on a tripod on the ground outside. Test conclusions were: the automatic steering would be capable of positioning the beam on targets located at 850 m, the NEROS field distance, and the expected noise equivalent signal at the same distance would be 26.5 ppb of ozone with a 34 second integration time.

NEROS Results: In the process of placement of the ILAMS in the EPA van, the ILAMS $CO_2$ laser tube was cracked. This effectively prevented participation in the NEROS since the system could not be returned to operational status by efforts made in the field. However, some tests were made to examine the quality of signal return from retro-reflectors placed, as originally intended, on a television antenna at various heights. A He-Ne alignment laser was used to give a visual display of the pattern of energy returned to the ILAMS. These patterns showed a significant variation among reflectors in the six lobe pattern of the return beam. Each of the six return lobes was displaced from the geometric centerline so that the return pattern in the best case had a torus shape and low energy near the center of the beam. In the worst case virtually no signal would have been returned inside the collecting aperture (Fig. 17).

Final System Status: Due to the limited funds remaining after the NEROS, the ILAMS was returned to EPA for transfer to EPA's inhouse contractor Northrop Services, Inc. (NSI). The system was placed in operational status and a demonstration test was performed over a 350 m optical path. The beam steering performed satisfactorily, but the laser output power was low. The responsibility for correcting this problem was assumed by NSI.

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## SECTION 3

## RECOMMENDATIONS

There are two areas of effort which deserve additional attention in dealing with the ILAMS. One is the testing of the system in its present configuration with the possible replacement of the $CO_2$ laser tube which appears to be slightly bowed and is likely responsible for the present low power output from the system. The testing should be a dedicated attempt to run the system over a period of time with no pressure to perform in a field test. This is the only way to objectively judge the feasibility of the laser-based long path approach to atmospheric monitoring. The second area of effort is the updating of the system with state-of-the-art components which would improve the system performance, e.g. a waveguide laser of much smaller size and alternative signal processing procedures to correspond to simpler wavelength modulation techniques. This second area of effort should only be pursued if the advantages of a long path monitor are actually needed to pursue EPA's current objectives.

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## SECTION 4

## FUNCTIONAL DESCRIPTION OF ILAMS

The ILAMS is completely described in General Electric reports[2,3] which should be referred to for detailed information. The system consists of the following units: a laser, a mini-computer, a teletype, and the interface electronics.

The laser will be described by referring to Figure 1. The lasing cavity follows a zig-zag path starting from $M_1$ to $M_2$ to $M_3$ to $M_4$ to the diffraction grating to $M_4$ to $M_5$ to $M_6$. The lasing lines are selected by a mask which has four separate apertures placed in front of the chopper (Fig. 21). The chopper blade has four fixed slots at different radii such that the apertures are opened in succession as the chopper rotates. Hence, each line lases for a time period equal to 1/8 of the chopper rotation period about 2.5 milli-seconds.

The laser output beam follows a path from $M_7$ to $M_8$ and through $L_1$ and $L_2$ to the beam splitter. Part of the output energy passes through the beam splitter to $M_9$ where it is focused on the reference detector. The remainder of the output beam is reflected off the beam splitter to $M_{11}$, $M_{12}$ and the telescope output mirror $M_{13}$. The beam traverses the measurement path and is returned by a retro-reflector to the telescope and back through the beam splitter to the signal detector.

The chopper position signal and the signals developed by the two detectors are fed to the interface electronics for input to the mini-computer. The first computer operation is to form a ratio between the return signal and the reference signal. An automatic gain control then adjusts the signal such that the largest of the four ratios is equal to 1/2. The logarithms of the four ratios are calculated and multiplied by -1000. This information is printed on the teletype with each data printout. The computer program also multiplies each logarithm by a pre-selected weighting factor and calculates the appropriate differences which are also printed by the terminal. The difference of the weighted logarithms of the ratios should be proportional to the ozone concentration.

The computer software permits the operator to set a number of parameters such as; the weighting functions, data printout rate, number of data points to be averaged, system time constant, and scaling constants. The basic requirement is that the system measures the difference in absorption between two lines with known absorption coefficients over a known optical path. The difference in absorption is a measure of the ozone concentration.

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## SECTION 5

## REDESIGN OF THE ILAMS

## DEMONSTRATION AND ACCEPTANCE TEST AT EPA CONTRACTOR SITE

The ILAMS demonstration and acceptance test was conducted at the G.E. facility in Syracuse, N.Y. during Nov. 1978. The plan was to devote one week to instruction and one week to the acceptance testing. During the instruction period the following items were covered:

1. Laser turn "on" and "off" procedure.
2. Spectroscopic determination of lasing frequencies.
3. The measurement of beam overlap.
4. Procedures for cleaning all mirrors.
5. Optical alignment procedures including the retro-reflectors.
6. Procedures for loading the programs into the computer and the use of the teletype output terminal.
7. Procedures for changing the program parameters.
8. Procedure for changing the data channel assignments.

The acceptance test was primarily an observation of the variation in the return signal with no ozone present. The low ozone concentration in the ambient air was confirmed by the chemiluminescent monitors. Measurements were made using retro-reflectors at 670 meters and 50 meters for periods of 4, 8, and 24 hours. The difference in variation of the signals returned from the two positions was not very well defined. In fact, unless the alignment was done very carefully, it appeared that the noise with a period less than one hour was greater from the close retro. The reason for this was not apparent until later.

Several tests were run with periods of 5 to 6 hours in an attempt to quantify the low frequency system noise. The results of an overnight "hands-off" test run from 5 pm Nov. 8 to 8 am Nov. 9, 1978, represented the best summary of the system performance.

The measured equivalent, one kilometer path, variation in ozone concentration determined by summing the difference in transmission between two pairs of closely spaced wavelengths is as follows:

1. The least variation in a one hour period 9 pm to 10 pm = 5ppb
2. The maximum variation in a one hour period 12 midnight to 1 am = 45 ppb.
3. The maximum overnight variation from 1:30 am to 6:30 am = 102 ppb.
   These numbers represented the system performance at the conclusion of the acceptance-test.

UNIVERSITY OF MICHIGAN - LABORATORY ANALYSIS - DEC. 1978 THROUGH MARCH 1979

The ILAMS was delivered to the University of Michigan on December 5, 1978 by a General Electric representative. The equipment was set up and operated in the High Altitude Engineering Laboratory. It was demonstrated that all the system components, the computer, power supply, water circulator, data readout devices, and the laser functioned properly. The system was operated in the laboratory with essentially a zero path length and the noise was observed. The observed noise had equivalent amplitudes as great as ± 50 ppb (1 km path) with periods as long as several hours, roughly equivalent to that observed in the acceptance testing. This level of spurious ozone concentration variation was unacceptable for the routine measurement of ozone, i.e. a 5 ppb long time variation was considered acceptable. The first task was to examine the equipment and attempt to determine the source of the noise. As a result of the very low frequency noise periods, each experimental observation had to be conducted over time periods approaching one day.

The basic approach to the investigation was to systematically reduce the length of the optical path and the number of elements in the path between the retro-reflector and the detector. The steps followed in the investigation were as follows: (Refer to Fig. 1)

1. The retro-reflector was placed directly in front of the telescope. This made the path length essentially zero and eliminated atmospheric turbulence as a cause of the problem.
2. The optical system was completely re-aligned using a helium-neon laser as a tracer. This was done to insure that the beam center line was as close as possible to the design center of all the optics.
3. Optical apertures with diameters nearly equal to the beam diameter were placed in front of both lenses. This virtually eliminated the possibility of over-filling any of the mirrors.
4. The telescope was removed from the system and replaced by a single flat mirror which returned the beam directly to the beam splitter. The noise remained unchanged. At this point the beam splitter became a prime suspect.
5. The beam splitter was repositioned and masked top and bottom to prevent stray light from reaching the detectors. The noise continued to persist.
6. The zinc selenide beam splitter was replaced by a KRS-5 beam splitter. This was done to determine if the anti-reflection coating was contributing to the problem. The answer was, "No."
7. The beam splitter was replaced by a front surface aluminum coated mirror and the beam was split by adjusting its physical position. This experiment demon- strated that the beam splitter was not at fault.
8. The cooling water recirculation pump was replaced with a pump of a different design and a reservoir was added. The objective was to maintain a more constant laser temperature and a more constant power output. However, it did nothing for the fundamental problem.
9. The ballast resistor cooling system was replaced with a slightly modified design to prevent voltage breakdowns and to reduce electrical noise. Again there was no effect on the system noise.
10. The zinc selenide windows on the detectors were removed. A dramatic effect was observed. The system noise was reduced by an order of magnitude. The system was tested for a period of 8 hours with a maximum equivalent noise variation of 5 ppb. The results are shown in Figs. 2 and 3.

The optical effect which was the source of the system zero drift or noise is very well known. In fact, it is common in infrared systems for two reasons: one, the index of

refraction of the optical materials is usually quite high which leads to high reflections and two, the window polishing techniques are similar to those used for ultra-violet components, which give surface flatness of high precision ($\lambda/10$).

Normally, etalons must be very carefully made in order to achieve the required precision. However, if a window normally intended for use in the visible is used in the infrared, the required precision may inadvertently be obtained. The window as an etalon is shown in Fig. 4.

This sketch assumes that the window is perfectly flat which, of course, is not the case. However, it illustrates that a very small variation in the angle of incidence could produce a large modulation of the output signal. An equivalent noise level of 5 ppb ($\frac{1}{1}$km path) represents an absorption difference for the two lines at 1056 $cm^{-1}$ and 1054 $cm^{-1}$ of 0.6%. This modulation could be simulated by a phase shift of 0.5° between the two wavelengths being compared. In the idealized case shown in the sketch a 0.5° phase shift translates to a change in the angle of incidence of something less than 0.001 degrees.

The problem can be completely avoided in any future designs by simply wedging the windows.

## SECTION 6

## PARTICIPATION IN NEROS

### INITIATION OF NEROS EFFORT

At about the same time that the zero drift problem of the ILAMS was solved plans were being formulated for the summer 1979 North East Regional Oxidant Study (NEROS). The overall purpose of NEROS was to develop models which could be used for predicting the long range transport of air pollutants. During the early planning stages, it was suggested that a long path laser designed to measure ozone might be used to determine both the height, formation time, and break-up time of the nocturnal inversion. This assumed that a 1000 foot tower could be located for mounting the required retro-reflectors. If the inversion information were available, one of the current theories regarding the transport of air pollutants could be tested.

The essence of the theory is that those pollutants generated in a metropolitan area during the daylight hours can be trapped under a subsidence inversion. However, shortly after dark, they are cut off from the ground by the formation of a nocturnal inversion. Then, during the night, the polluted air mass, caught between the two inversions, is transported many miles down wind by the geostrophic wind until the nocturnal inversion is broken up the next morning by surface heating. This could explain the observation of high pollutant levels in some remote rural areas. The opportunity to test this theory and to demonstrate the measurement capabilities of the ILAMS was an exciting possibility.

### SYSTEM MODIFICATION FOR THE NEROS, MAY 1, 1979 - JULY 31, 1979

The decision to use the system in the field study was made on April 1, 1979. However, the funding to carry out the project was not available until May 1, 1979. An extremely tight schedule had to be adhered to in order to complete all the tasks in the required time necessitating a compromise on some of the original tasks. However, the necessary tasks relating to the modification were completed.

The tasks as originally outlined were as follows:

1. Select site location and make on site arrangements.
2. Design and build beam steering mechanism.
3. Design and build alignment aids.
4. Design and build retro-reflector mounts.
5. Design and build optical table mounting.
6. Modify laser cooling system.
7. Modify computer program and integrate beam steering commands.
8. Calibrate and test system over long path.

The modification tasks will be discussed in the order listed above.

## Site Selection

The site selection was dictated by the experiment requirements. The basic objective of the experiment was to measure the height of the nocturnal inversion, the time of its formation, and the break-up time. It had been estimated that the inversion usually formed at a height of from 200 feet to 1000 feet above the average terrain. The ideal structure would have been a tower 1000 feet high with retro-reflectors placed at 200 foot intervals. The proposed set up is shown in Fig. 5.

The inversion was to be located by making a series of measurements in fairly rapid succession from the top retro-reflector to the bottom (a complete data set in 5 - 10 minutes). If the ozone vertical profile was as indicated, an approximate inversion location could be determined.

A second requirement determined by the NEROS experiment was the geographical location. The NEROS study area covered Pennsylvania, New York, and most of New England. The ideal location would have been 50 miles up-wind of either Philadelphia or New York. It was apparent from the outset that either a T.V. or F.M. tower would be required. Fortunately, information regarding T.V. and F.M. stations was readily available in a T.V. factbook[6]. The choice was quickly narrowed to four stations. After making telephone calls to the manager of each station, the decision was made to use station WGAL-TV in Lancaster, Pa. The tower was 1360' above the average terrain, 823' above the ground, and located 2.25 miles NE of Hallam, Pa.

After selecting the station, a trip was made to the location in order to: (1) pick and arrange for a van location, (2) locate a contractor to install electric power, (3) arrange phone service, (4) locate a contractor to install the retro-reflectors, and (5) make tower measurements in order to design retro-reflector mounts. All of these arrangements went very smoothly thanks in a large part to the management of station WGAL-TV.

## Beam Steering Mechanism

The design and construction of the beam steering mechanism was the most critical item in the modification effort. It could not be compromised and it had to be completed in less than two months. The design was completed in three weeks, and the construction was started almost immediately and completed on schedule.

The design requirements were as follows:

1. The system including the beam steering device had to fit the existing General Motors van by mounting on the existing optical table and extending through the existing roof opening.
2. Azimuth adjustment: $360^{o} \pm .0015^{o}$
3. Elevation adjustment: $2^{o}$ to $25^{o}$ above horizon $\pm .0015^{o}$
4. Beam diameter: 6' to match telescope
5. Beam control: - Azimuth - Manual, Elevation - Microprocessor and Computer Control
6. Beam Slew Rate: - 30 seconds or less between positions.
7. Elevation axis: - Adjustable to eliminate all azimuth adjustments after initial set-up.

The General Motors van in which the system was to be installed was carefully measured during an April visit to RTP. Fortunately, it was possible to incorporate the system in the van with very minor modifications. The optical table on which the laser was mounted was kinematically mounted on the optical table in the van. A very large two-axis optical mount was created using the two optical tables. This permitted the precision alignment of the optical table in two axes.

The azimuth adjustment was done by incorporating a bearing plate in the periscope, Fig. 6, vertical tube. The tube had a coarse adjustment which could be set to a few degrees. A clamp was locked in place and the final adjustment was done with a 2" diameter micrometer which could be read to .0001 inches. A setting to .00015 inches met the accuracy requirement.

The vertical adjustment was done with a stepping motor. The stepping motor was incorporated into a worm gear drive which was purchased as a package. The gear drive package and the associated microprocessor were purchased from Aerotech. The original specification on angular accuracy was based on setting the beam at one kilometer to $\pm$ 1 inch. However, the Aerotech drive single step was 0.25 arc seconds or $0.004^{\circ}$. This step was 3 inches at one kilometer which was acceptable. A major consideration in the decision to purchase this equipment was the delivery schedule.

In order to meet the time schedule, both the elevation mirror and the fixed bottom mirror were taken from another EPA system. The length of the elevation mirror limited the maximum angle to $23^{\circ}$ which had to be accepted.

The beam slew rate, set by the microprocessor, was 500 steps per second. The system could scan the entire vertical range in 12 seconds. This was more than adequate.

In order to guarantee that the laser beam traced a straight line from the top to the bottom of the tower two adjustments were required. One adjusted the elevation mirror to be parallel to the elevation axis and the other adjusted the axis to be perpendicular to the vertical beam. These adjustments were made with 2 inch diameter micrometer heads which were quite satisfactory.

## Alignment Aids

In order to align the laser beam on the retro-reflector target it was necessary to provide alignment aids. The aids used were (1) a spotting telescope and (2) a He-Ne laser.

A removable kinematically mounted mirror was designed to fit between the telescope and the periscope. The spotting telescope was mounted so that its line of sight was perpendicular to the center line of the laser beam (Fig. 7). The He-Ne laser and the spotting telescope were clamped in the same mount and fastened to the table.

The original alignment was performed by "walking" a retro-reflector to a position about 100 feet away from the laser while maintaining the return signal. The removable mirror was put in place and the He-Ne laser was adjusted to follow the center line through the periscope and to strike the retro-reflector. The retro-reflector was then moved to positions approximately 100 yds and 200 yds away, and minor adjustments of the He-Ne laser were made. After the initial adjustment, the retro-reflector could be placed in any position and quickly aligned first with the spotting telescope and finally with the He-Ne laser.

## Retro-Reflector Mounts

The specifications on the retro-reflector mounts were as follows:

1. Lightweight as possible - maximum 2 pounds.
2. Adjustable in azimuth and elevation
3. Easily clamped to a 5 inch diameter pipe.
4. All clamping and adjustments to be done with one-hand.

The design which met all the requirements is shown in Fig. 8.

The mounts were made of aluminum with a stainless steel clamp.

At the time of installation the retro-reflectors were fastened to the mounts. The tower climber had two small canvas buckets about 10 inches in diameter and a foot deep. Two complete assemblies were placed in each bucket and the two buckets were suspended from his belt. The installation was made by rotating the rear portion of the 5 inch diameter clamp 90° around the pivot point shown. The front portion of the clamp was pressed against the 5 inch diameter tower leg. The rear portion of clamp rotated back to the closed position and the spring loaded clamp was fastened. The spring in this position was only lightly loaded so that azimuth adjustments could be made by pressing lightly on the retro-reflector. When the correct position was found the toggle clamp was turned 1/2 turn which locked the azimuth position. The elevation position was set by pressing on the retro-reflector and locked in place using the 2 1/2" diameter clamp handle provided.

Although these clamps operated very well, there are two items which should be noted for future experiments. One, the retro-reflectors if they are aluminum coated should be sealed with a transparent plastic. The surfaces deteriorated very badly during the four week study period. Two, very large birds were attracted to the retro-reflectors as landing sites. During the last few days of the study one of the retro-reflectors was misaligned in elevation due to this activity.

## Optical Table Mounting

The laser optical table was mounted on the van optical table as shown. (See Fig. 9). The sizes and proportions of the two tables were such that a two-axis leveling mount could be designed with the pivot points as shown. Clamps were provided for each pivot so that the two tables could be clamped together when the van was in motion.

## Laser Cooling

The plasma tube and the ballast resistors were cooled by flowing water through a glass jacket. G.E. provided a commercial circulator cooler for use with the system. They, however, did not use the cooler because the line starting transients would usually disable the computer. Their location had tap water available which was run through the cooling jacket.

At the U of M this option was not available but the transients were successfully minimized. However, there were two other problems: (1) the reservoir was inadequate and (2) the circulation pump often required priming. The second fault was serious because it often led to severe overheating after the initial turn on. A new pump and a new storage tank were incorporated into the system.

## Computer Program Modifications

The original system modification plan was to steer the beam to the four separate retro-reflectors in succession, measure the ozone concentration, and calculate the inversion height all through computer control. This was a task which we believed could be done in the available one month period.

The only hardware required in addition to the Aerotech EC2 stepping motor drive was a general purpose interface for the PDP-11. An interface model DR11-C was obtained from MDB Systems, Inc. The hardware was assembled and the stepping motor was operated via the computer teletype input. However, in order to have the computer drive the stepping motor to the selected location and collect data, these commands had to be incorporated into the existing program.

The existing program was written in assembly language on a large scale computer at G.E. The program was then transferred to paper tape and the program entered in the PDP-11 through the paper tape reader attached to the system. The existing assembly language program was obtained from GE and modified using the U of M computing facilities. However, the equipment available at the U of M for transferring the assembly language program to paper tape became disabled which made this step impossible.

Fortunately, the Aerotech EC2 had front panel controls which allowed the operator to select a given position and drive the stepping motor to that position. The stepping motor could be driven by the operator to the four selected positions and the positions noted on the teletype read out. In view of the time constraints, it was decided that this type of operation could be acceptable.

## Calibration and Long Path Tests

Although the system modification required a maximum effort in order to be completed in time for the NEROS, a determined effort was made to conduct field tests which would provide confidence that the system would perform as planned. The planned calibrations and tests were as follows:

1. Calibrate the system in the laboratory using a multi-pass cell to simulate a long path and use a chemi-luminescent monitor to measure the ozone concentration.
2. Assemble the completely modified system in the laboratory garage and perform a second calibration.
3. Set a retro-reflector at the maximum available range (210 meters) and measure the beam diameter.
4. Set a second retro-reflector at approximately half the maximum range and compare the signal levels. Estimate the field study return signal.
5. Simulate the field study return signal by aperturing the retro-reflectors at the available range.
6. Determine the effect of beam displacement on ozone concentration calculations.

The results of these experiments will be reviewed in order.

## Laboratory Calibrations

The laboratory calibration was performed by removing the telescope input mirror and adjusting the multipath cell so that the beam from the beam splitter entered the cell.

The beam passed through the cell and was returned at the cell exit by a small flat mirror (Fig. 10).

The total number of cell passes was 48 and the total path was 68.8 meters. Since, the system output is the product of path length and concentration, the expected output output could be simulated with a large concentration. The normal summer time maximum concentration is 120 ppb ($C = 120 \times 10^{-9}$) and the expected path length was 1700 meter ($L = 1.7 \times 10^{3}$ cm). Hence, the maximum expected $CL = 2.04 \times 10^{-2}$ ATM-cm. In order to simulate this product in the calibration cell a concentration of 2.965 ppm would have been required. The available ozone generator could produce a concentration of 2.1 ppm, equivalent to 85 ppb at the expected range. Since all the absorption measurements were well within the linear absorption range, it was decided that the 2.1 ppm generator would be satisfactory. A typical calibration based on the difference between the $P_{12}$ and $P_{24}$ lines of the $CO_2$ laser is shown in Fig. 11. The calibration was performed several times with similar results.

After the equipment was moved from the laboratory to the garage, the system was re-assembled and another calibration was performed.

The difference between the laboratory and the garage calibrations can be noted in Table 1. The calibrations have been reduced to absorption coefficients and compared to published values.

TABLE 1

ILAMS CALIBRATION COMPARISON-ABSORBTION COEFFICIENT

| Lines Differenced | Laboratory | Garage | Published Values |
|---|---|---|---|
| $P_{12}$-$P_{24}$ | 10.0 $Atm.^{-1}cm^{-1}$ | 10.0 $Atm^{-1}cm^{-1}$ | 11.5 $Atm.^{-1}$ $cm^{-1}$ |
| $P_{12}$-$P_{10}$ | 4.7 " | 6.3 " | 6.2 " |
| $P_{26}$-$P_{24}$ | 3.6 " | 4.4 " | 5.3 " |

It should be noted that the laboratory calibration does not agree very well with the published values, whereas the garage calibrations indicate better agreement. The primary difference between the two set-ups was that during the laboratory calibration a flat mirror was used to return the beam through the multi-pass cell, whereas in the garage calibration a parabolic mirror was used to re-focus and return the beam. If the beams are not uniform in cross-section and there was any aperturing of the beam, a calibration error could be produced. The use of a parabolic mirror at the cell exit would reduce any aperturing of the return beam and the associated errors. We believe that this explains the difference between the two calibrations and that the garage calibration is the most reliable.

The most convenient way to use the calibrations is to convert the printout unit values to ozone concentration at a range to be used, e.g. the minimum resolvable ozone concentration change using the pair of lines $P_{12}$-$P_{24}$ and a 179.9 meter path length is 2.8 ppb. A set of typical values is given in Table 2.

TABLE 2

MINIMUM RESOLVABLE OZONE CONCENTRATION

LINE PAIR VS. RANGE

| Line Pair | 179.9 meters | 850 meters |
|---|---|---|
| $P_{12}$-$P_{24}$ | 2.8 ppb | 0.59 ppb |
| $P_{12}$-$P_{10}$ | 4.4 ppb | 0.93 ppb |
| $P_{26}$-$P_{24}$ | 6.3 ppb | 1.34 ppb |

Long Path Measurements

The purpose of the first long path measurement was to determine the beam diameter at a distance great enough so that the beam overfilled the retro-reflector. The maximum available range of 210 meters was selected for the test. Each of the four retro-reflectors to be used in the field study was set at this range and the return signal was measured. This established the relative reflectivity of each retro-reflector. The return signal was maximized on one retro-reflector and the face was blocked. A second retro-reflector was placed in four quadrant positions adjacent to the blocked retro-reflector (Fig. 12).

TABLE 3

RETRO-REFLECTOR SIGNAL RETURN VS. ANGULAR DISPLACEMENT

| Retro-Reflector Position | Test 1. | Test 2. | Test 3. | Test 4. |
|---|---|---|---|---|
| 0, original position | 0.7v | 0.6v | 0.6v | 0.6v |
| 1 | .07v | .32v | .07v | .24v |
| 2 | .04v | .20v | .05v | .20v |
| 3 | .24v | .07v | .1v | .16v |
| 4 | .22v | .14v | .6v | .35v |

The experiment was repeated four times. The results are given in Table 2. As can be seen from this data, it was very difficult to steer the beam to the center of the original retro-reflector. The best results are shown in test #4. The beam was estimated to be 25 cm wide by 20 cm high at 210 meters equal in angle to 4.2 arc minutes by 3.3 arc minutes. Based on this data, beam positioning to 1 arc minute should have been adequate.

The second long path experiment was to measure the return from two retro-reflectors placed at a significantly different distance. Using these measurements, the return signal from a retro-reflector at the field study distance of 850 meters was estimated. The experimental arrangement is shown in Fig. 13.

A basic assumption underlying this experiment was that the beam was uniform in cross-section and the profile was approximately gaussian. The experiment was conducted in the following manner:

1. The reflectivity ratio between the two reflectors $R_1$ and $R_2$ was determined by measuring the ratios of the two signals returned from precisely the same location at a distance of 210 meters. The ratio was $R_1/R_2 = 1.16$.
2. $R_1$ was placed at 118.6 meters and $R_2$ was placed at 179.9 meters and the maximum return from each was measured. The measured signal from $R_1$ = 0.68 volts and the measured signal from $R_2$ = 0.38 volts. There should be an inverse relationship between the signal received and the distance to the reflectors carried to some power between 1 and 2, depending on the degree of collimation of the source. This can be expressed as follows:

$$\frac{0.68 \text{ volts } (R_1 \text{ signal})}{0.38 \text{ volts } (R_2 \text{ signal}) \times 1.16 \text{ (Reflectivity ratio)}} = \left[\frac{179.9_m \text{ (Distance to } R_2)}{118.6_m \text{ (Distance to } R_1)}\right]^x$$

where x is the experimentally determined power.

$x = 1.04$.

Assuming that the beam diverges uniformly from 118.6 meters to 850 meters, the signal voltage expected from 850 meters was calculated as follows:

$$V_F = 0.68 \text{ volts}/(850m/118.6m)^{1.04}$$

$$= 0.088 \text{ volts}$$

This result was interpreted in the following manner:

1. Based on the calibration (Fig. 11) each print out integer for $P_{12}$-$P_{24}$ equals 0.59 ppb at 850 meters (for $P_{12}P_{10}$ this value is 0.93 ppb and for $P_{26}P_{24}$, 1.34 ppb.)
2. The noise signal for the best $P_{12}$-$P_{24}$ data at 179.9 meters was 9 units which is equivalent to 5.3 ppb of ozone at 850 meters.
3. If the ratio of the signal returned at 179.9 meters to the signal expected at 850 meters is 0.44 /.088 = 5.0, then the expected noise signal at 850 meters should be 5.3 x 5.0 = 26.5 ppb. This assumes that the noise is inversely proportional to the signal. This result was at best marginally satisfactory. If the ozone levels were very high, reasonable data might be obtained.

A third long path experiment was conducted to simulate the retro-reflector aperture at longer ranges. This was done by placing aperture stops of varying diameters over the retro-reflector at the 179.9 meter distance. The results are shown in Fig. 14. As can be seen, the return signal increased to a maximum with a three and one-half inch aperture. No satisfactory explanation for this effect was found.

## Beam Displacement Experiments

As a result of previous laboratory experiments and measurements made by GE of the energy distribution across the beam (Ref. 3, p. 70), there was reason to believe that the calculated ozone concentration would change with the beam position on the retro-reflector. Hence, the basic experiment was to displace the beam from a nominal centerline position into four quadrant positions and compare the measurements. If there was zero ozone present, then the off-set resulting from steering the beam off the centerline could be measured and a correction applied. The purpose of the measurements was to determine if such a correction could be made. The measurement conditions were as follows:

Date - July 13, 1979
Time - 1 pm - 4 pm EDT
Retro-Reflector - 5 inch diameter corner cube, 5 arc-sec
Mfg. by Precision Lapping
Distance to Retro-reflector - 179.9 meters
ILAMS - as modified by High Altitude Engineering Lab - U of M
Signal Amplifier gain - Position # 3
Reference Amplifier gain - Position # 1
Return signal at amplifier output - 0.4 volts
Data collection - teletype printer
Data printout rate and data accumulation - one set per 34 seconds

The measurement procedure was as follows:

1. The beam was positioned on the retro-reflector at maximum output position and the azimuth control micrometer was moved in the same direction to the nearest .001 inch (0.2800 inches). Data set 5 was collected.
2. The micrometer was displaced by an arbitrary amount and returned to the same setting (0.280 inches). Data set 7 was collected.
3. The azimuth control was displaced in the negative direction far enough to reduce the returned signal by a factor of 2. Data set 9 was collected.
4. The azimuth control was displaced far enough in a positive direction to pass through the maximum position. Data set 10 was collected.
5. The azimuth control was returned to 0.2800 and the elevation control was moved 4 steps in the negative direction. Data set 12 was collected.
6. The elevation control was moved 4 steps in the positive direction. Data set 14 was collected.
7. The beam was re-positioned for maximum signal return. Data set 15 was collected.

The data collected for each set was averaged and the sigma values associated with each average were calculated. The averaged values are tabulated in TABLE 4. The physical relationship between the beam cross-section and the retro-reflector cross-sections are shown for the data collection condition (Fig. 15).

The initial conclusion from an examination of this data was that the system could produce the information required by the NEROS experiment. This was based primarily on an examination of data set 15. In this set, the sigmas associated with the signal return from each line are very good. The best sigma is 0.3% and the worst is 1%.

The data in TABLE 4 shows that steering the beam off the center line caused large off-sets, $P_{12}$-$P_{10}$ (see sets 7 and 9). The beam could be repositioned to within less than the sigma for three of the four lines (see sets 5, 7, and 15.)

The interpretation placed on these results was that the off-set errors could be measured when no ozone was present, and the corrections applied to the field measurements. The designed positioning accuracy of 0.25 arc minutes would essentially eliminate the positioning errors.

ILAMS Mobile Installation

A General Motors Corporation (GMC) 26 foot van which had been used by EPA during several previous field experiments was made available for the NEROS experiments. The van was equipped with an optical table whose feet extended through the floor for mounting on concrete pads on the ground. In this way the table was vibrationally isolated from the van. There was an opening in the roof through which the beam steering mechanism could extend.

The critical van dimensions had previously been measured and the optical components were all designed to fit the available space. The equipment fitted as planned. However, some modifications were made to the protective covers in order to provide more clearance. The clearance between the van and the optical table depended on the level of the ground. The electronic components were mounted in standard racks. The van was equipped with two standard rack size compartments. Hence, most of the installation involved only the clamping of cables and the mounting of components into the racks.

During the laser installation, which required four people, a high voltage electrode was broken off the laser tube. This required a repair by a glass blower. After the repair, the system was successfully evacuated and a normal discharge was achieved. No lasing was observed. The conclusion was that one of the optical components had been slightly misaligned. Since misalignment might occur during the 600 mile trip to Pennsylvania and alignment would have to be done in the field anyway, it was decided to transport the equipment to the field study site before attempting realignment.

NEROS FIELD STUDY - JULY 30, 1979 THROUGH AUG. 31, 1979

Location - Hallam, Pennsylvania.

The ILAMS completely assembled in a 26 foot GMC motor home arrived on location July 30, 1979. The initial set-up proceeded on the planned schedule: the van was located in a level position, concrete pads were placed under the optical table, the power and phone service were connected, the distance from the van to the tower was measured, the height of the tower and the angles to all the retro-reflector positions were measured. (Fig. 16) The measured height was verified by the WGAL staff.

The tower climber was contacted and the retro-reflectors were installed with no problem. Each reflector was equipped with a small sighting aid which consisted of two

small peep holes spaced six inches apart. The climber reported that he was able to align all the retro-reflectors with no problem. It was noted, when the reflectors were removed about four weeks later, that the surfaces had corroded. In any future installation, some type of transmitting material should be used over the reflector.

Laser Alignments

The laser alignment procedure began on Tuesday, Aug. 7 and by Thursday, Aug. 9, the system was lasing on three lines. This was very disappointing at the time. However, it represented the best laser performance during the field study. The following two weeks were spent in trying to improve the alignment and also to understand the system. This was an extremely frustrating experience. The laser has 8 reflecting surfaces inside the lasing cavity, 14 optical elements external to the cavity, and 7 optical alignment elements. No laser alignment aid was provided with the original system. The He-Ne laser used as an alignment tool and the insertion mirror had to be held in place with masking tape and putty. This arrangement was not satisfactory for operation in a field environment.

Following the field trip, it was discovered that the vacuum pump used with the laser had inadvertently been interchanged during the van installation. The pump supplied by G.E. was a Welch Model 1405 B with a pumping speed of 60 l/min compared to the 20 l/min pump used during the test. This factor also contributed to the difficulty in obtaining strong lasing lines.

Retro-Reflector Evaluation

In order to align the ILAMS laser on the tower retro-reflectors it was necessary to boresight the He-Ne laser with the ILAMS laser. Before carrying out the boresighting operation, it was decided to put the He-Ne laser on a tripod beside the van to see if a visual return from a retro on the tower could be noted. Aligning the laser on a reflector turned out to be a relatively easy task. It was noted that the reflected beam could be seen over a fairly large solid angle, but the maximum intensity seemed to be off to one side of the laser. The same experiment was repeated at night with a 22" x 30" poster board directly in front of the laser. A one-inch diameter hole was made in the center of the board to permit the laser beam to exit and the return beam to be observed. The return patterns were both surprising and interesting. A few nights later under a clear moonless sky, the experiment was repeated with a camera on a second tripod. Several exposures were tried and the best photographs are shown in Fig. 17.

The dotted line on the photographs outlines the system's optical aperture. It is apparent that most of the returned energy is <u>not</u> collected. The return energy is divided into six lobes; this is most easily seen in photo 4. The beam striking the reflector is divided into three parts and each part is reflected off the two opposite mirrors. Hence, each return lobe has a mirror image. This effect is partially responsible for the unusual return patterns but is most apparent in photo 1. The centerline of each lobe diverges from the optical centerline of the reflector by an amount dependent on the dihedral angle error. Retro-reflectors have been studied in detail[7-14] and the problem noted here has been examined. These studies indicate that the dihedral angle errors must be no more than a few arc seconds if a large fraction of the total energy is to be collected. In many situations more energy can be collected by using smaller and more precise reflectors. This is particularly true if multiple reflectors can be used. The NASA moon ranging experiment[15] is an excellent example of the use of multiple reflectors.

The ILAMS system design should have used either higher precision reflectors or larger collecting optics for greater energy collection.

## Long Path Alignment

The long path alignment required that the ILAMS laser be boresighted with the He-Ne laser and the spotting telescope. Once the bore sighting was complete, a return signal was expected whenever a He-Ne return could be observed. The same procedure used in the Ann Arbor test was followed. After adjusting the system on a reflector at 100 meters distance, an attempt was made to receive a signal from one of the tower retro-reflectors. No signal could be observed.

A reflector was then placed at 240 meters. The return signal from this position was 1.1 volts with all amplifiers set as they were during the Ann Arbor test. This was almost twice the signal received in Ann Arbor and the reflector was only 2 inches in diameter. Attempts were made again to obtain returns from the tower reflectors. Very careful raster scans were made across each reflector, but no return signal was observed. Arrangements were made to set up a reflector in an adjacent field at a distance of 500 to 600 meters. The result, once more, was no return signal. The conclusion was that the return signal was not being collected by the optics. The explanation was that the return signal was in the form of a torus, expanding as a function of range. At some point beyond a critical range, perhaps 250 meters, the center of the torus becomes larger than the collecting optic and the return signal drops very rapidly.

## Beam Steering Evaluation

During the boresighting operation a few tests were performed to evaluate the performance of the beam steering mechanism. The He-Ne laser was used as a visual indicator and the beam was steered across each of the tower reflectors using the azimuth control micrometer and the step motor drive.

The azimuth control had slightly more resolution than required. The beam could be positioned in at least 5 positions on the reflector. The elevation control of 0.25 arc minutes was ideal for the range. The beam could be positioned directly on the reflector: a single step dropped the intensity about a factor of two and two steps dropped the intensity an order of magnitude.

The elevation commands operated very well. Once the four reflector positions were determined, the beam could be returned to the same positions on command provided the same direction was used to overcome the backlash. If the system is to be used in the future, the backlash should be improved.

The combination of the elevation mirror adjust and the elevation axis adjust made it possible to align precisely the laser scan with the tower. The beam could be positioned on each of the four reflectors with no adjustment of the azimuth control. The beam steering mechanism was judged to have met all the design requirements.

## Auxilliary Measurements

The ozone concentration was measured at the van with a DASIBI monitor furnished by EPA for the study. The monitor was calibrated before and during the study by an audit team from the Research Triangle Institute. The ozone concentration was also measured

at the base of the tower during the day with a portable AID monitor. This monitor was calibrated by the same audit team. The data collected by these monitors was previously furnished to EPA and will not be included in the report.

## SECTION 7

## POST FIELD STUDY

The effort that followed the field study was extremely limited due to a lack of funding. The decision was made to correct the most glaring errors and to use any remaining funds to have a student take measurements.

The tasks which were carried out were as follows:

1. A He-Ne tracer beam system was designed and constructed for use in making both the cavity and external optics alignments.
2. A new grating mount was designed and built.
3. A retro-reflector literature survey was done by the student. A listing of the pertinent papers is given in the references.
4. The data collected before the NEROS field study was re-examined.
5. The replacement of the original plasma tube with a spare tube furnished by G.E. was begun.

The He-Ne laser alignment system is sketched in Fig. 18 and 19. The alignment system can provide a tracing beam for two separate conditions:
(a) A beam is provided to align the mirrors in the cavity (Fig. 18) and
(b) A beam is provided for the external optics alignment through the telescope and periscope (Fig. 19).

The alignment system consisted of the following parts: a He-Ne laser, a laser mount, two steering mirrors, a $90^{o}$ two surfaced injection mirror, and an X-Y translation mount. The laser and the two steering mirrors ($M_{18}$ and $M_{19}$) fastened to the mount and the mount was fastened to the optical table. Both of the steering mirrors were adjustable in two axes. This permitted the beam to be steered in angle and displaced in two directions.

The key element in the system was the injection mirror ($M_{17}$) which had two reflecting surfaces at $90^{o}$. The injection mirror was adjustable in two axes and the mirror mount was fastened by means of an extension arm to the X-Y translational stage shown in Fig. 19. Once the system was correctly aligned, the laser beam could be switched from the cavity alignment mode to the telescope alignment mode by moving the Y control on the translational stage. The alignment beam could be completely removed by moving the X control on the translational stage. The use of the translational stage was a design improvement developed by Northrop Services during the transfer of the equipment to EPA.

The grating mount originally used on the system was a standard two-axis mirror mount with a wedge to provide the nearly correct angle. The problem with this arrangement was that an angle adjustment also produced a displacement and there was no way to measure the position. The replacement grating mount rotated the grating around an axis parallel to its face and around another axis perpendicular to the first axis. Both adjustments were micrometer spindles. In order for the replacement mount to be incor-

porated, a special holder had to be designed to permit operation at $90^{o}$ to the intended mounting position. (See Fig. 20.)

The essence of the retro-reflector study was a determination of the trade off between reflector size and reflector accuracy. The retro-reflectors used in this study were constructed from three optical flats positioned optically and glued together. The cost of this construction becomes almost prohibitive beyond a tolerance of 3 arc seconds. In future designs it would be better to use electroformed reflectors two inches in diameter with a 2 arc second tolerance. Three of these units would be more efficient than a single 5 inch glued unit.

As a result of the retro-reflector study and the knowledge that the laser beam could be positioned in an unexpected manner, the Long Path Measurements prior to the NEROS field study were re-examined.

After re-examining the data it was noted that the sigmas were larger than expected, especially, those associated with the differences which are the measure of the ozone concentration. The specific points to be made can be observed in data set 15 TABLE 4, the best set available.

1) The estimation of the noise equivalent signal at 850 meters was based on the assumption that the sigma values should be inversely proportional to the signal or directly proportional to the log of the signal level. In set 15 the log ratios are as follows:

$$\frac{\ln P_{26}}{\ln P_{24}} = 1.38, \quad \frac{\ln P_{12}}{\ln P_{24}} = 1.61, \text{ and } \frac{\ln P_{10}}{\ln P_{24}} = 1.57$$

and the corresponding sigma ratios are:

$$\frac{\sigma P_{26}}{\sigma P_{24}} = 2.62, \quad \frac{\sigma P_{12}}{\sigma P_{24}} = 4.0, \text{ and } \frac{\sigma P_{10}}{\sigma P_{24}} = 5.33.$$

2) If the sigma values for set 15 are written in terms of ozone concentration for the data collected at 179.9 meters, the results are as follows:

$\sigma P_{12} - \sigma P_{10} = 11.4 \times 4.4$ ppb = 50.16 ppb

$\sigma P_{12} - \sigma P_{24} = 9 \times 2.8$ ppb = 25.2 ppb

$\sigma P_{26} - \sigma P_{24} = 6.3 \times 6.3$ ppb $\doteq$ 39.6 ppb

3) The sigmas associated with the differences are in every case larger than any of the individual sigmas and, in most cases, equal to the square root of the sum of the squares. This would imply that the noise source associated with one line is independent of the noise source associated with another line.

The implication of these observations is that the noise does not come from the usual

sources such as, the signal amplifiers, laser power supply, computer round off errors, turbulence along the path, etc. These results could be explained by an irregular and varying laser beam intensity pattern. It was known[2] that this laser had an irregular pattern, but it was assumed that by differencing very closely spaced lines the problem could be avoided. The conclusion based on these observations is that the problem still exists, but remains to be demonstrated.

The replacement of the original plasma tube was started by the student assigned to the project. However, it was not completed at the time of the system transfer to EPA.

The completion of the plasma tube installation and the development of the laser alignment procedure was primarily the work of Joachim Pleil of Northrop Services. He is the author of the following sections of this report.

## SECTION 8

## ILAMS TRANSFER TO EPA, JULY, 1980 - SEPT., 1980

The ILAMS modification work was terminated at the U of M as of May 31, 1980. The complete system, installed in a GMC van, was turned over to Northrop Services as of June 30, 1980 in Ann Arbor, Michigan and driven to the EPA-NERC at Research Triangle Park, North Carolina. The purpose of the research reported here was to complete those system modifications started at Michigan, to develop the necessary alignment and operating procedures, and to determine the feasibility for making successful long path ozone measurements. The modifications made are described in the following section and the operating procedures are described in the appendices.

### Modification of the Optical System

The initial inspection of the ILAMS upon arrival at EPA-RTP indicated that there were a number of minor problems. The water cooling jacket inlet for the plasma tube and the laser gas inlet had both cracked, the plasma tube Brewster windows and the vertex mirror showed appreciable damage, and the water cooler was in-operable.

The indicated repairs were made and a continued examination indicated that the following modification tasks should be carried out.

1. A new vertex mirror ($M_2$, Fig. 10) was required.
2. New Brewster windows ($B_1$ and $B_2$, Fig. 19) were required and the plasma tube mounting surface required additional lapping.
3. The pumping speed of the installed vacuum pump was too low and a replacement was required. (Problem discussed earlier.)
4. The new grating mount designed at the University of Michigan needed to be installed.
5. The He-Ne alignment system insertion mirror ($M_{17}$, Fig. 18) mount required redesign.

Task 1 -- The vertex mirror installation was carried out by first setting the alignment laser to pass the beam through the laser cavity. The old mirror was removed and the new mirror set in position. The new mirror had a copper base and required mechanical support and electrical insulation from ground. This was provided. The plasma tube was lapped and the tracer beam was periodically observed to make sure that the beam remained on the center of both $M_2$ and $M_3$ (Fig. 18). After the surface was lapped smooth and the alignment beam was correctly positioned, the mirror was glued into position. After the glue dried, the seal was leak checked.

Task 2 -- The same procedure used with the vertex mirror was used in lapping and glueing the Brewster windows.

Task 3 -- A 60 liter per minute vacuum pump was located and used to replace the 20 liter per minute unit installed in the van.

Task 4 -- The new grating was installed.
Task 5 -- The He-Ne alignment insertion mirror ($M_{17}$) mount was originally designed to fasten onto the output mirror mount ($M_1$). In order to change from the cavity alignment mode to the external alignment mode, the mount had to be rotated. The precision of this technique was not adequate.

The design modification was to fasten the insertion mirror mount to the X-Y translation stage by means of a cantilever arm. The Y motion of the translation stage permitted the switching of alignment modes without any other adjustments. The X motion permitted the withdrawal and repositioning of the insertion mirror with no other adjustments. In the external mode the He-Ne tracer could be used to align the telescope, target the retro-reflectors, and align the spotting telescope. The full alignment procedure is given in Appendix B.

Data Acquisition

The ILAMS data acquisition system consists of:

1. a digital chopper shaft encoder,
2. a computer interface containing a multiplexer, an analog to digital converter, detectors, and signal amplifiers,
3. a PDP-11/05 computer, and
4. a Teletype-paper tape reader used as I/0 device.

Initially, the computer and associated electronics were very erratic. This was attributed to a long period of inactivity as well as possible temperature, humidity, and electrical noise problems associated with the van installation. Basically unwanted noise pulses were being introduced to the computer which would lead to anything from strange printouts to a complete shut down. The problem was solved by developing definite procedures for loading the software tapes, setting the gain controls, setting the system parameters and assigning shaft positions. While the computer check out procedure was being developed, two significant system problems were noted. One, if the interior van temperature exceeded 90°F catastrophic software failure could occur and two, in the process of turning the system power off, transients could alter some of the control parameters. System power up and power down procedures developed to overcome these problems are described in Appendix C.

These residual problems with bringing the system online for actual measurements included the low power output of the laser. This was attributable to the misshapen laser tube (the replacement tube). The system was left with EPA's inhouse contractor (Northrop Services) for any additional effort.

## REFERENCES


1. W. A. McClenny et al., "Development of a Gas Laser System to Measure Trace Gases by Long Path Absorption Techniques", Contract No. 68-02-0757, EPA-650/2-74-046-b, July 1974.

2. R. J. Gillmeister and L. R. Snowman, "Carbon Dioxide Laser System to Measure Gaseous Pollutants", EPA-600/7-77-009, January 1977.

3. General Electric Company, "Instruction Manual for Modified Infrared Laser Atmospheric Monitoring System", Contract 68-02-1783, September 1978.

4. TV and FM Fact Book # 44, 1974-75 edition.

5. P. L. Bender et al., Science 182, 229 (1973).

6. Edson R. Peck, J. Opt. Soc. Amer. 38, 1015 (1948).

7. K. N. Chandler, J. Opt. Soc. Amer. 50, 203 (1960).

8. P. R. Yoder, Jr, J. Opt. Soc. Amer. 48, 496 (1958).

9. Edson R. Peck, J. Opt. Soc. Amer. 52, 253 (1962).

10. R. F. Chang, D. G. Currie, and C. O. Alley, J. Opt. Soc. Amer. 61, 431 (1971).

11. James L. Zurasky, Appl. Opt. 15, 445 (1976).

12. David A. Arnold, Smithsonian Astrophysical Observatory Special Report 382.

13. P. N. Slater and W. Weinstein, J. Opt. Soc. Amer. 48, 146 (1958).

14. B. J. Pernick, Rev. Sci. Inst. 45, 1344 (1974).

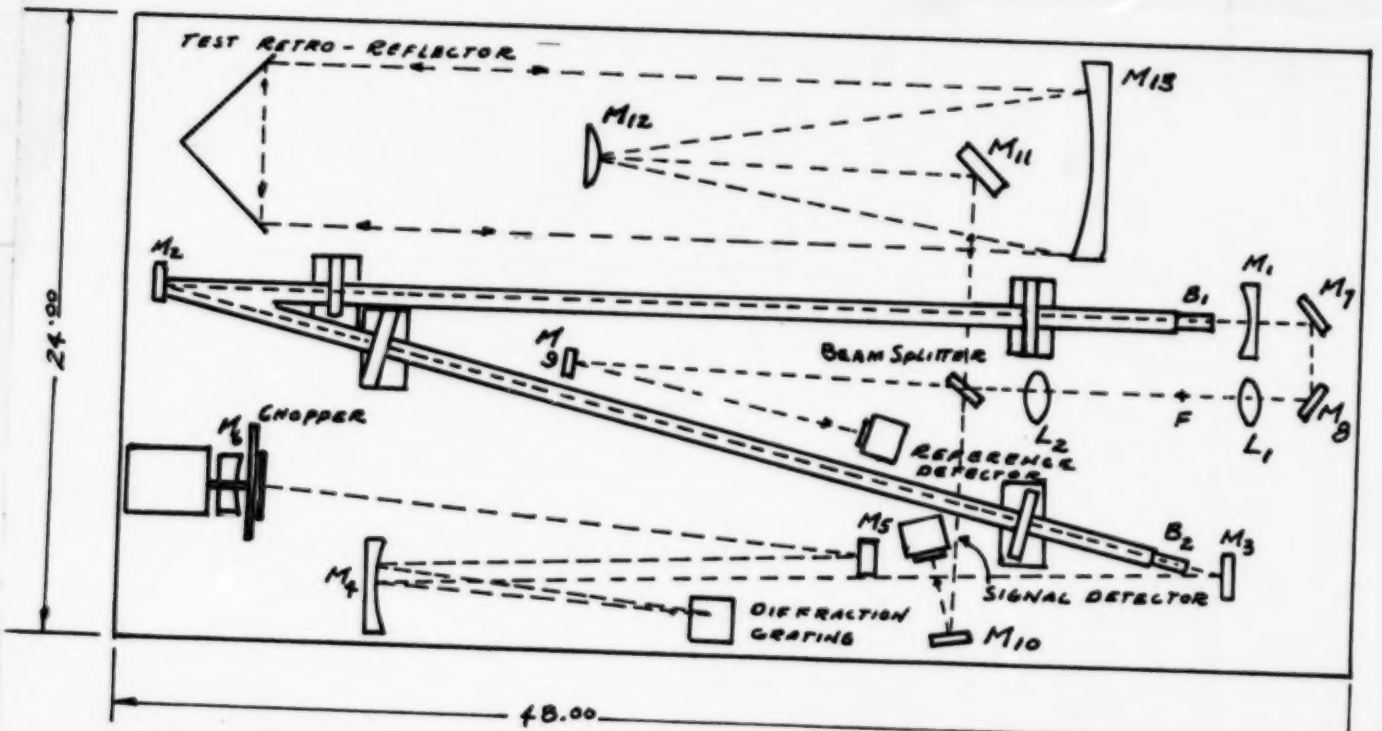



FIG 1 ILAMS OPTICS - LABORATORY TEST

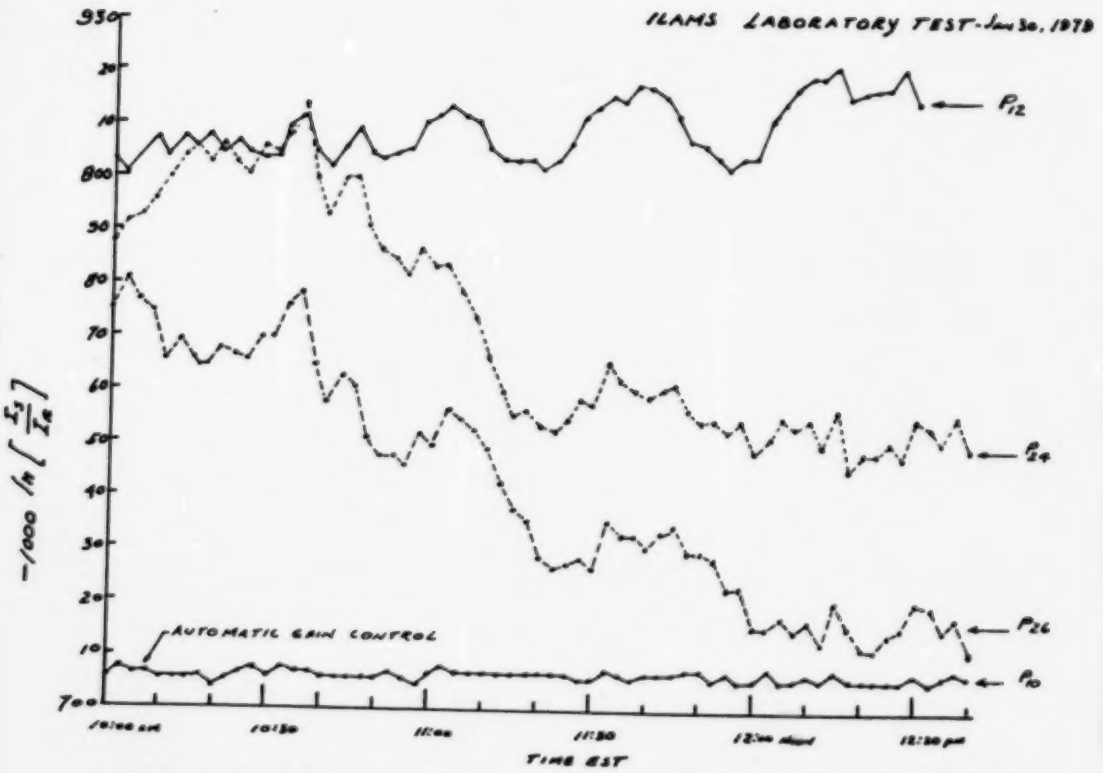



FIG. 2 MEASURED INTENSITIES – ZERO PATH WITH DETECTOR WINDOWS

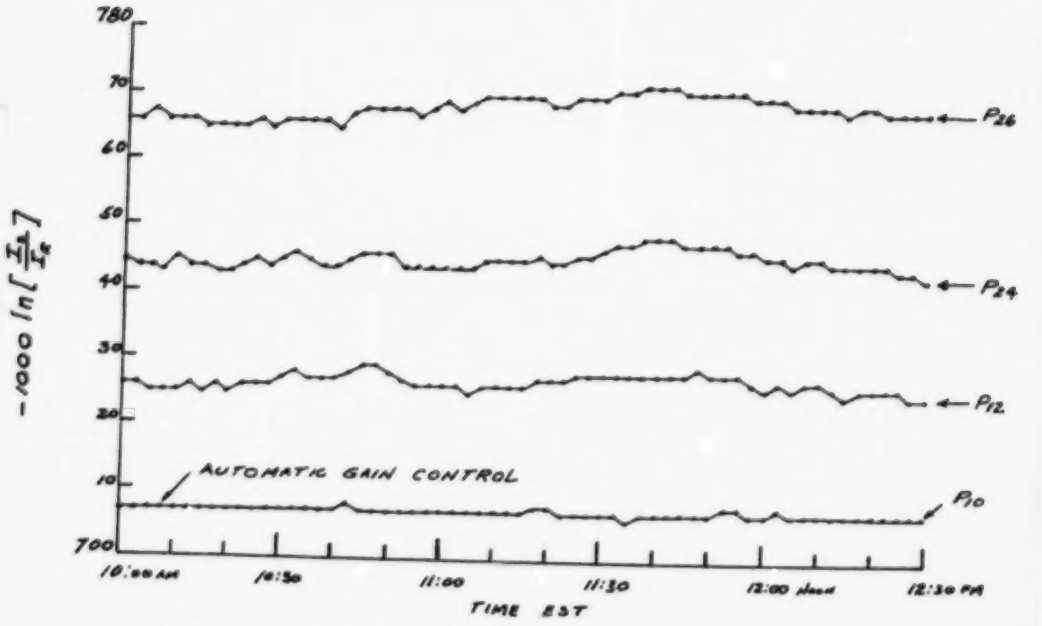
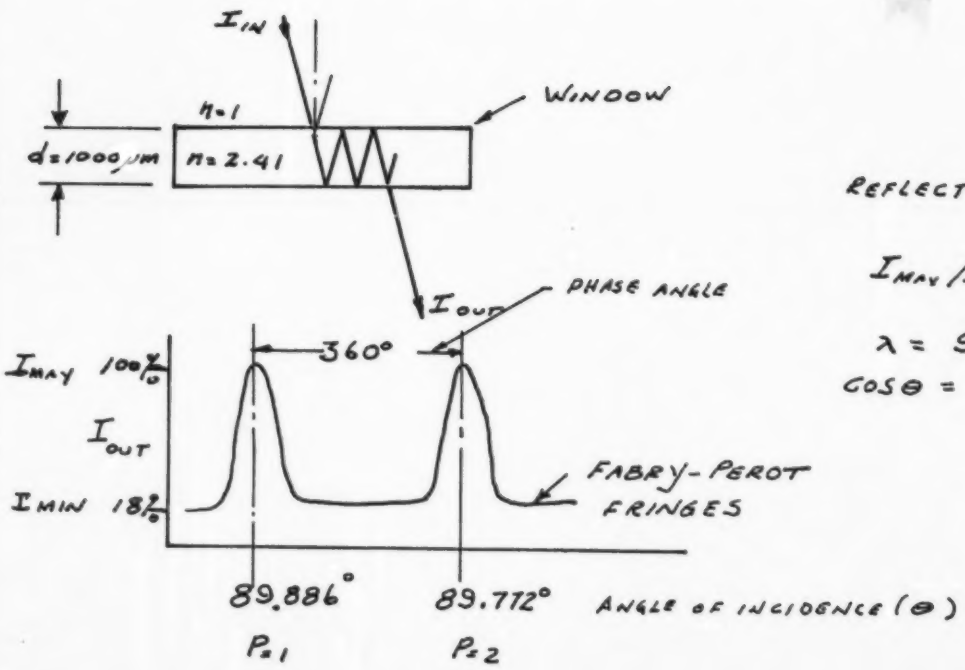



FIG. 3 MEASURED INTENSITIES – ZERO PATH WITHOUT DETECTOR WINDOWS




REFLECTIVITY $R = \left(\frac{2.41-1}{2.41+1}\right) = 0.41$

$I_{MAX}/I_{MIN} = \left(\frac{1+R}{1-R}\right)^2 = 5.71$

$\lambda = 9.6\,\mu m$

$\cos\theta = P\lambda/2nd$

FIG. 4 FABRY-PEROT WINDOW EFFECT

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TOP OF IMAGE AREA
BOTTOM OF IMAGE AREA OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS

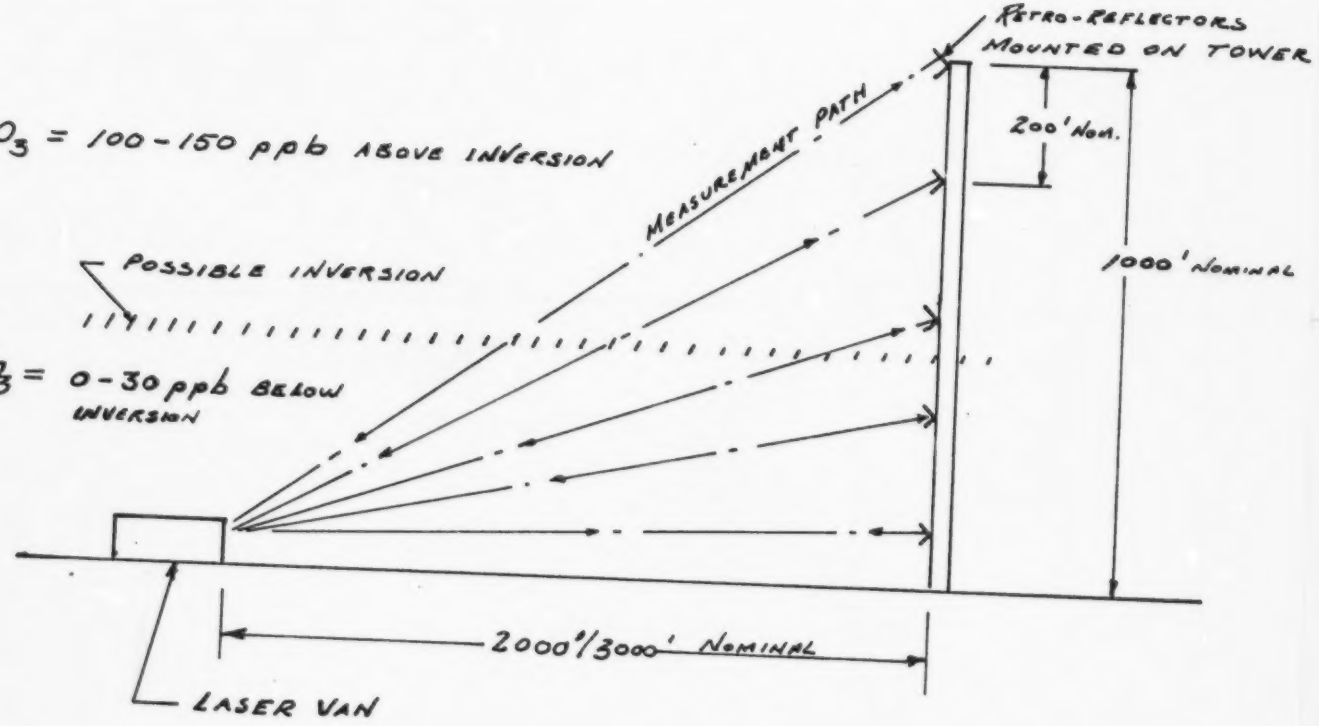


FIG. 5 PROPOSED NEROS EXPERIMENT

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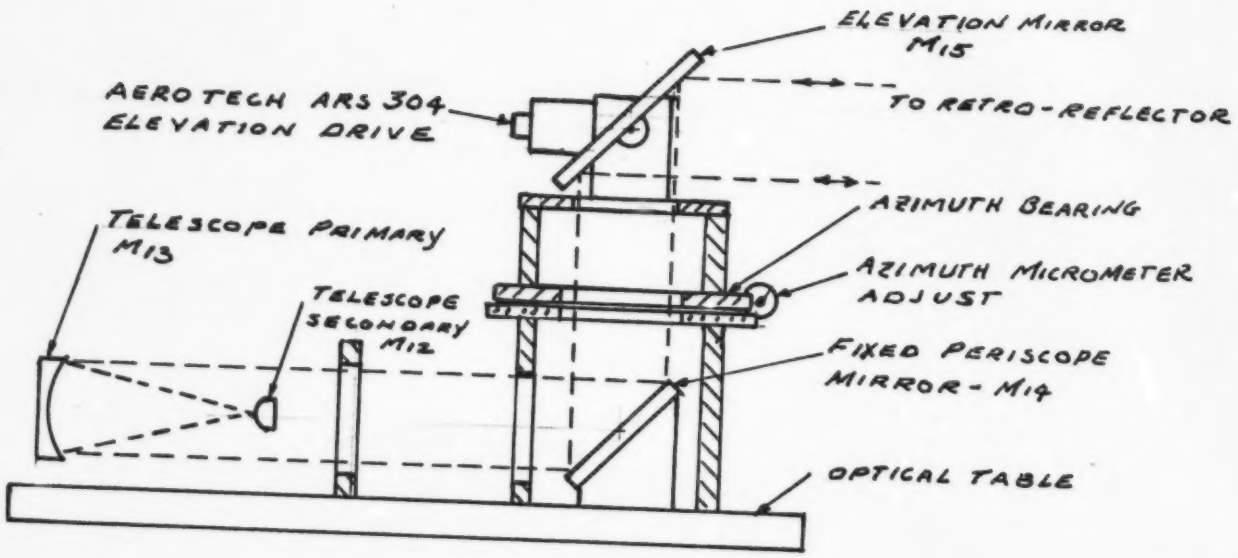


FIG. 6 PERISCOPE SKETCH

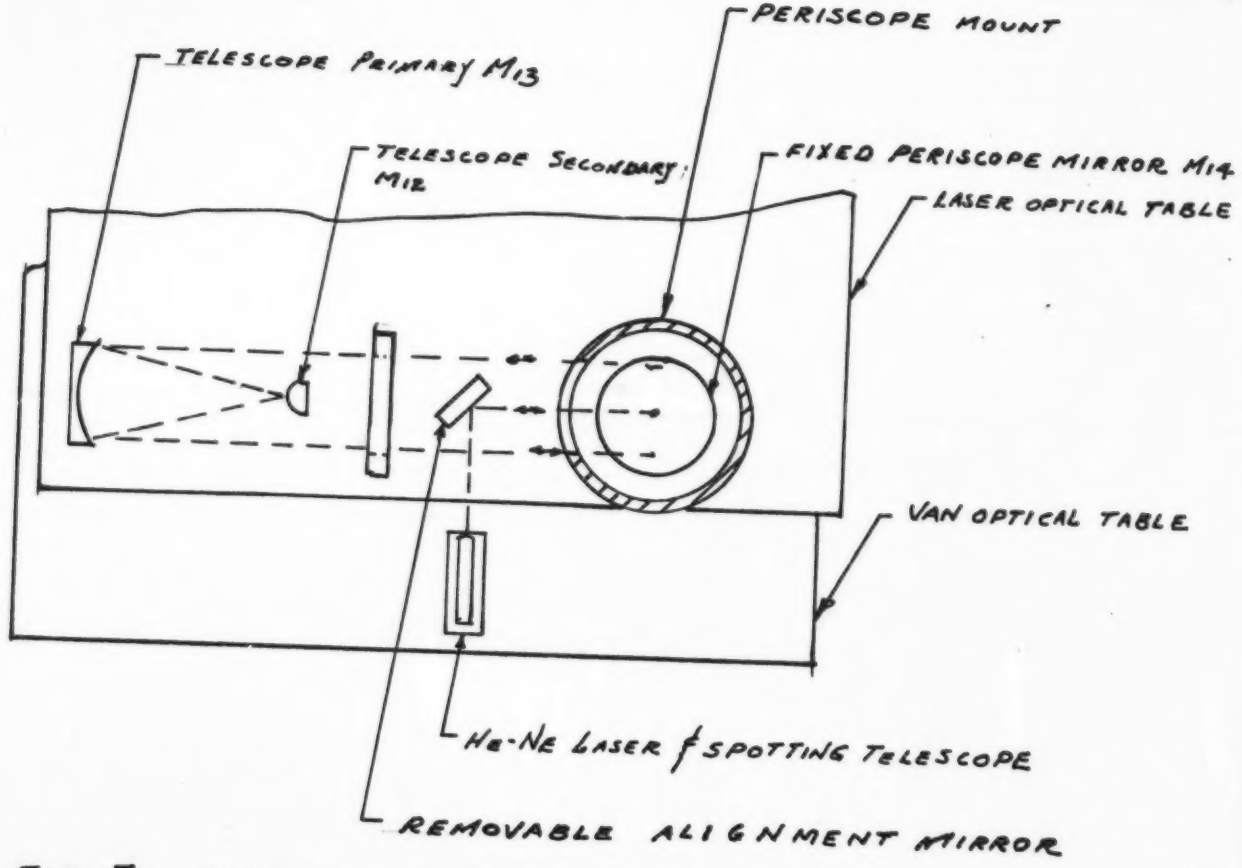


FIG. 7 SPOTTING TELESCOPE LOCATION

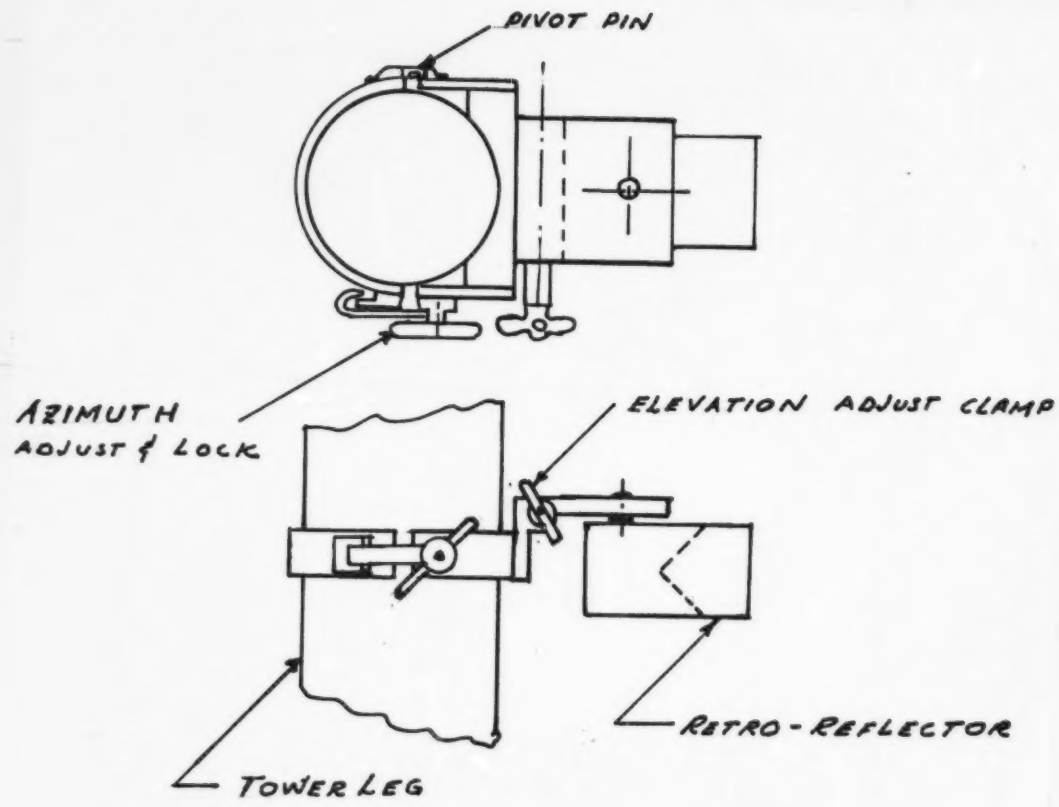


FIG. 8 RETRO-REFLECTOR CLAMP

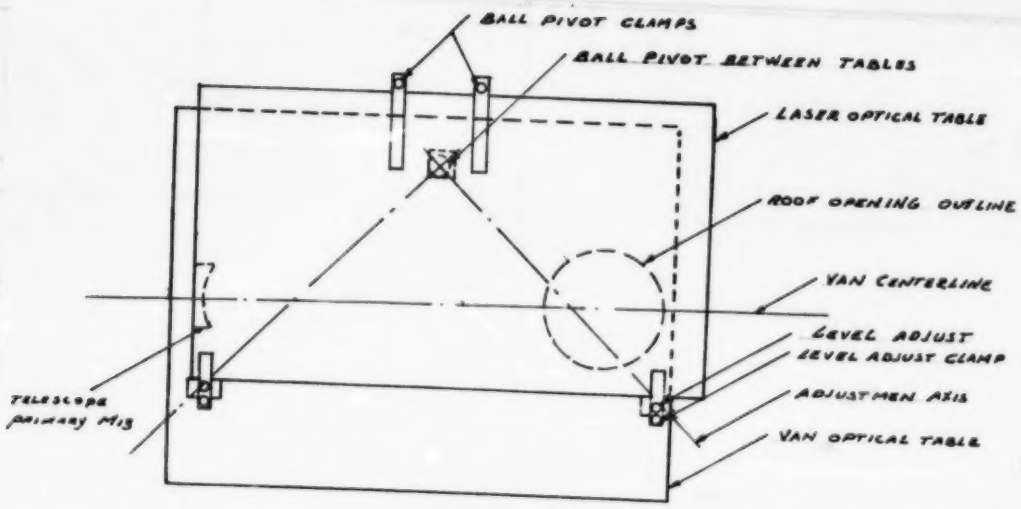


FIG. 9 VAN OPTICAL TABLE MOUNTING (TOP VIEW)

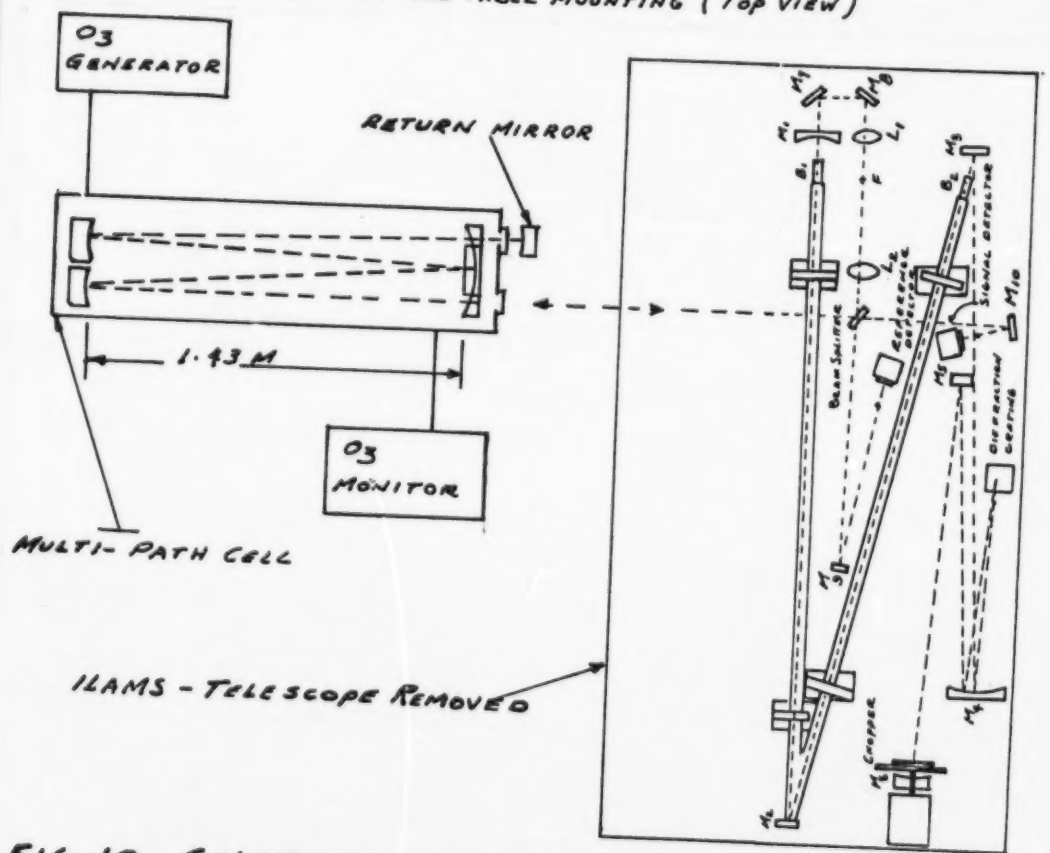


FIG. 10 CALIBRATION SET-UP

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FIG. 11 LABORATORY CALIBRATION ($P_2 - P_{24}$)

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".5"



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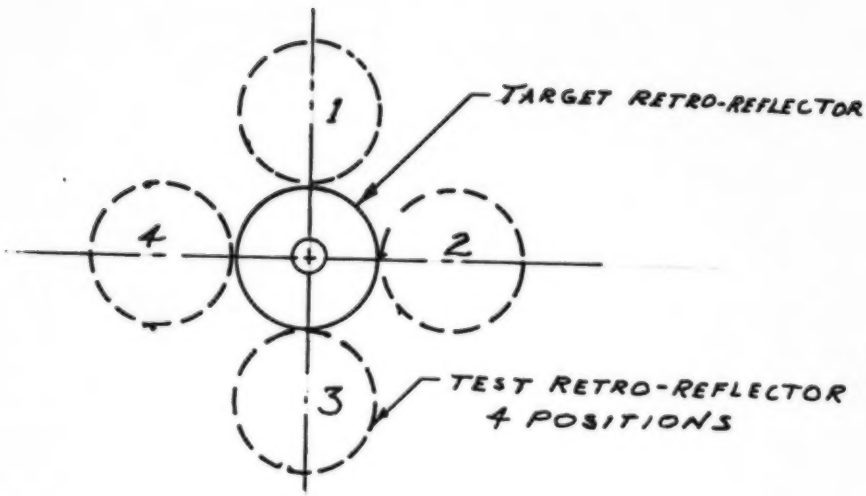


FIG. 12 BEAM DIAMETER TEST

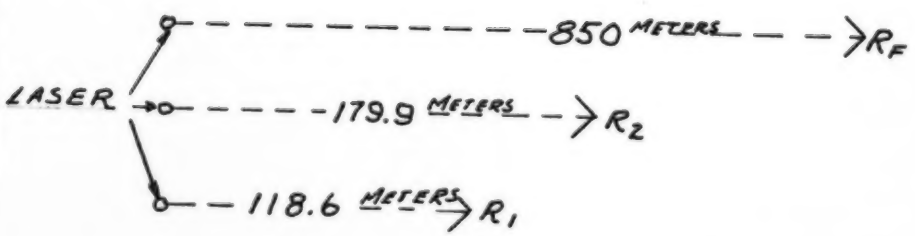


FIG. 13 RANGE TEST POSITIONS

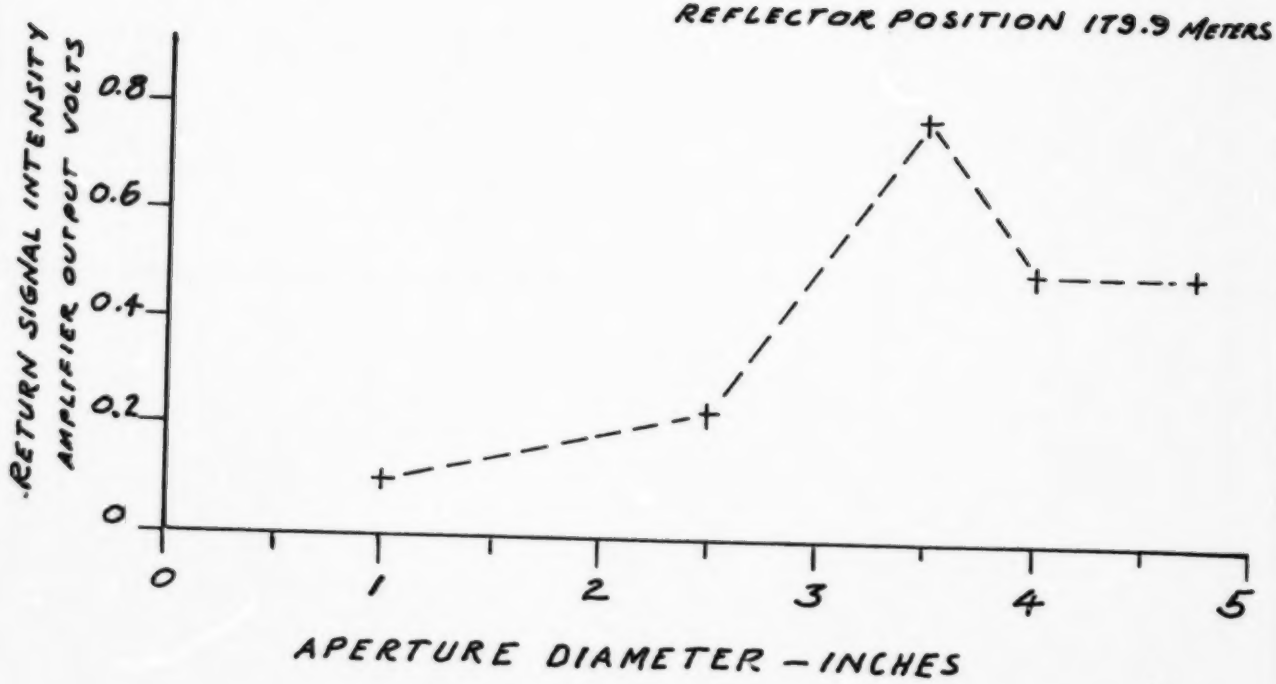


FIG. 14 REFLECTOR APERTURE TEST

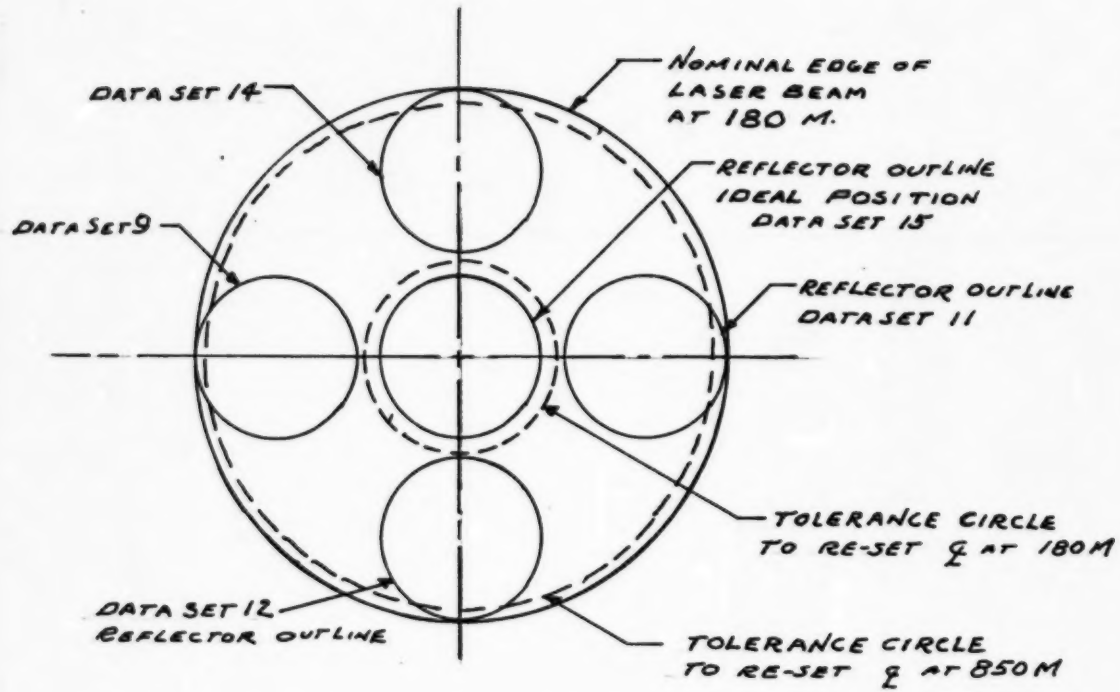
NOMINAL EDGE OF LASER BEAM AT 180 M.
DATA SET 14
REFLECTOR OUTLINE IDEAL POSITION DATA SET 15
DATA SET 9
REFLECTOR OUTLINE DATA SET 11
TOLERANCE CIRCLE TO RE-SET ℄ AT 180 M
DATA SET 12 REFLECTOR OUTLINE
TOLERANCE CIRCLE TO RE-SET ℄ AT 850 M

FIG. 15 BEAM - REFLECTOR RELATION

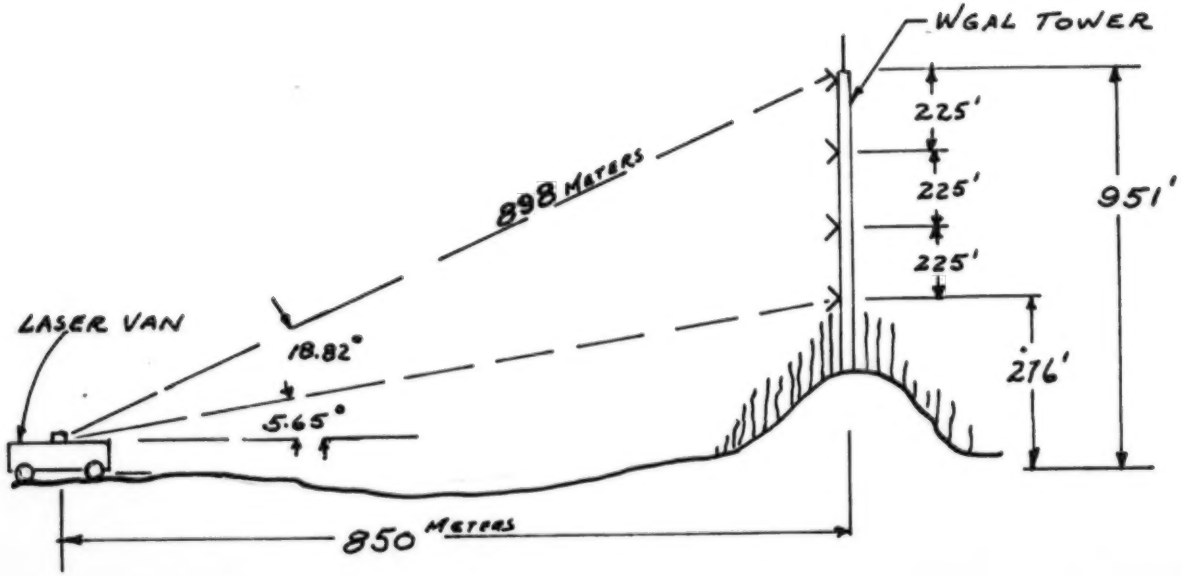


FIG. 16 MEASURED OPTICAL PATH LOCATIONS ON WGAL TOWER

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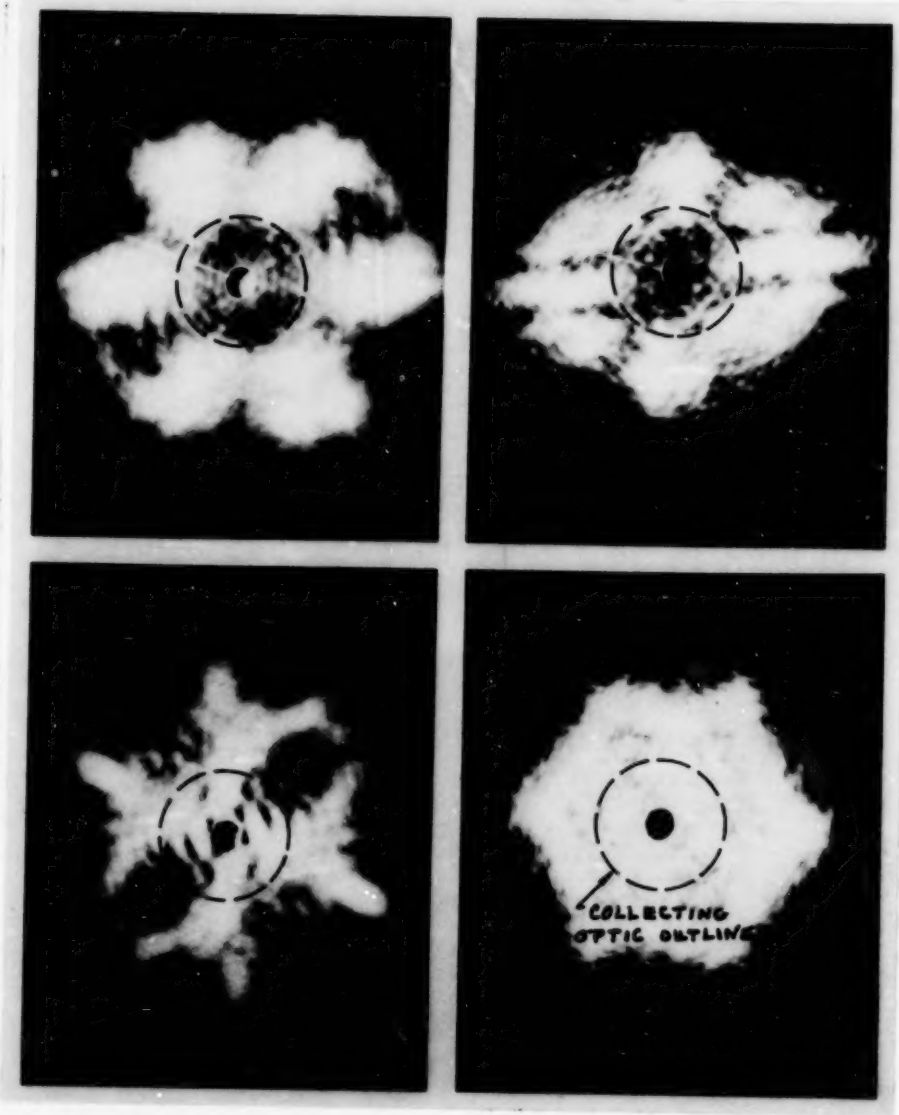


FIG. 17 RETURNED HE-NE BEAM FROM TOWER REFLECTORS

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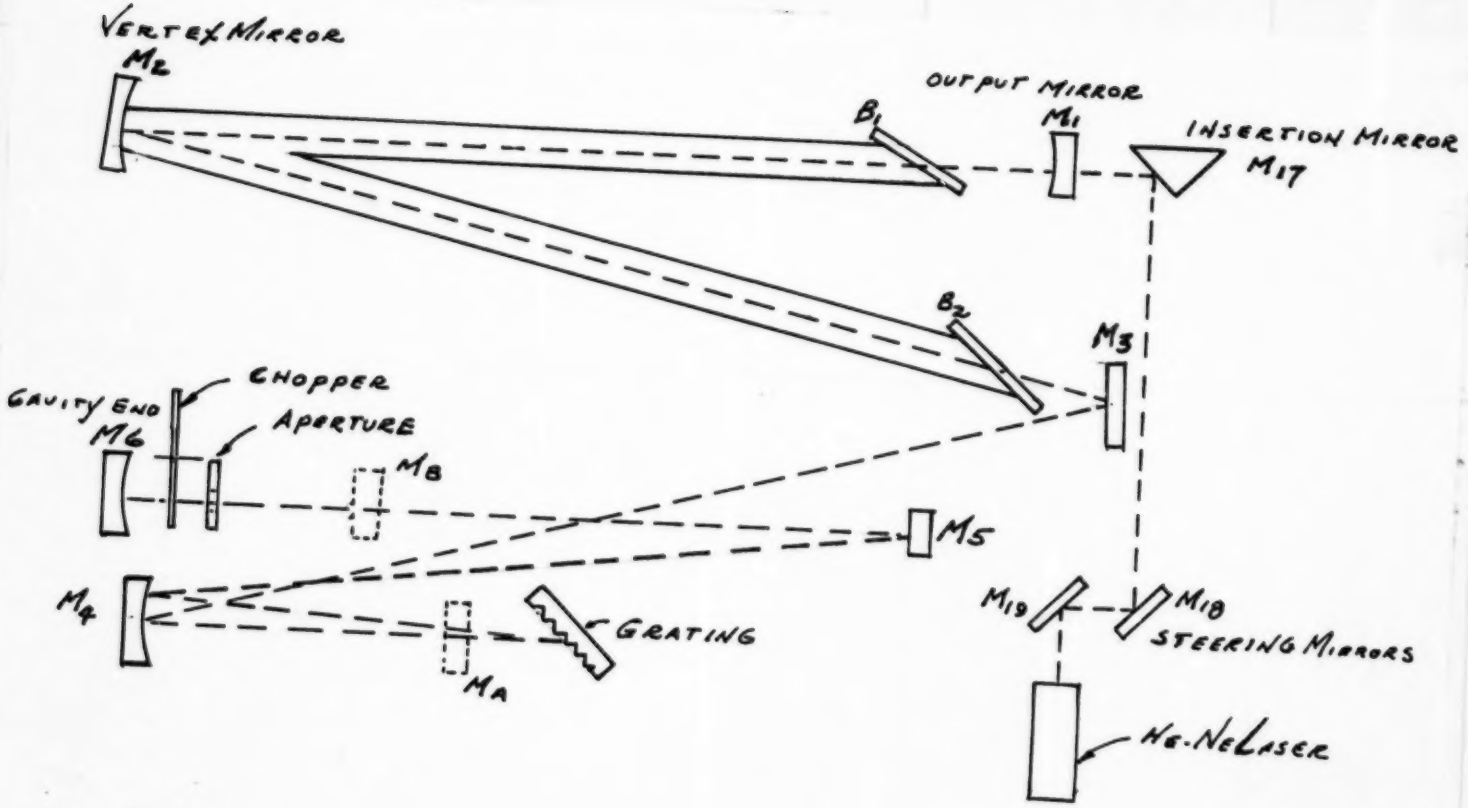


FIG. 18 ILAMS CAVITY OPTICS - ALIGNMENT MODE

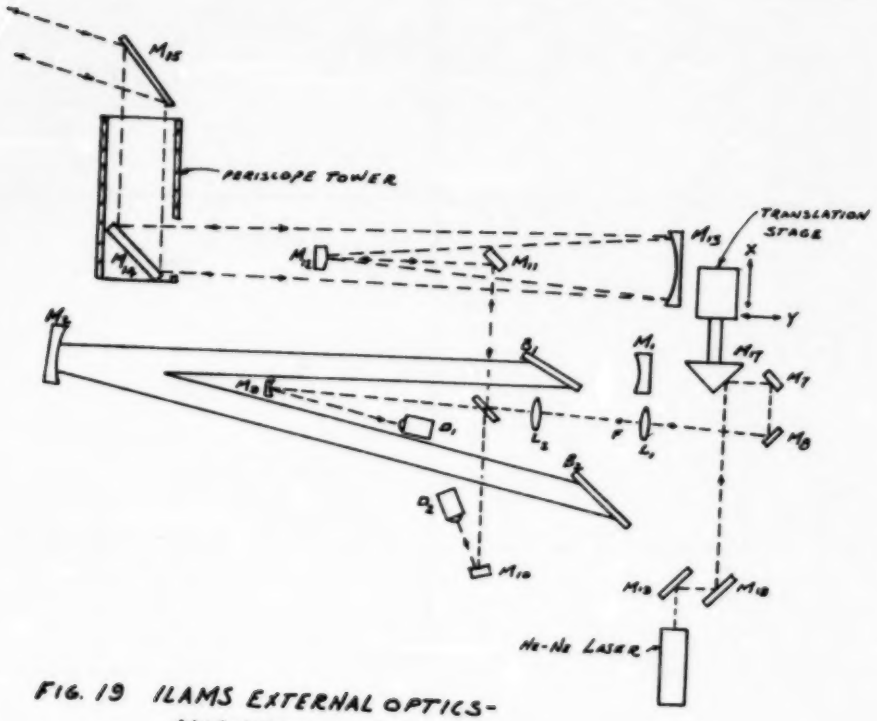


FIG. 19 ILAMS EXTERNAL OPTICS-
ALIGNMENT MODE

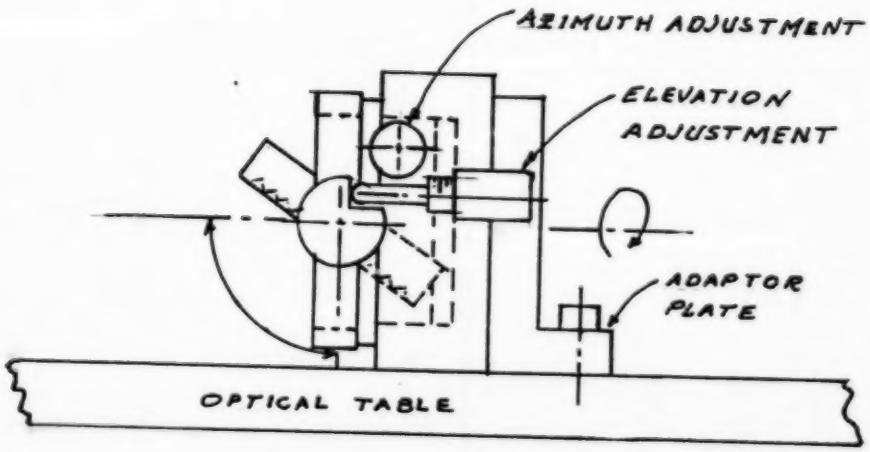


FIG. 20 GRATING ROTATIONAL ADJUSTMENT AXES

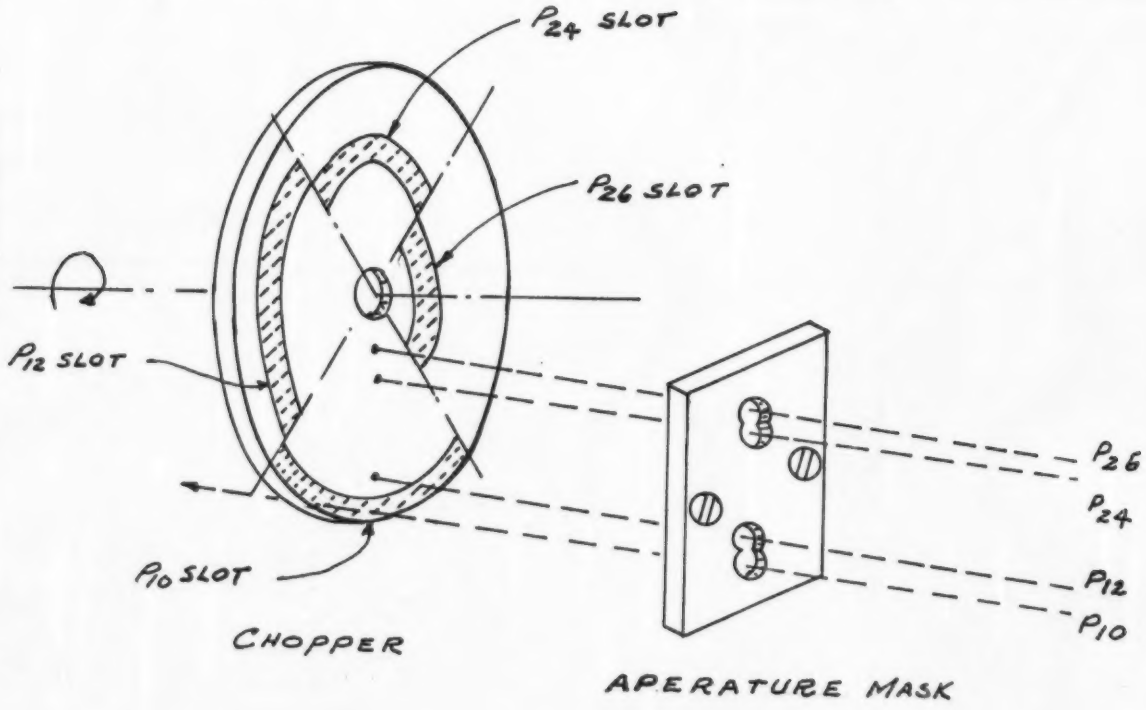


FIG. 21 ILAMS FREQENCY SELECTION

# TABLE 4

## SELECTED ILAMS DATA — JULY 13, 1979

LOCATION - HIGH ALTITUDE ENGINEERING LABORATORY-A, M.
RETRO-REFLECTOR DISTANCE — 179.9 METERS
RETURN SIGNAL - PREAMP OUTPUT — 0.4 VOLTS
DATA OUTPUT RATE — 34 SEC / POINT
SIGNAL AMPLIFIER — POSITION 3
REFERENCE AMPLIFIER — POSITION 1
OUTPUT = $-1000 \ln [I_S / I_R]$

DATA SET #5

BEAM POSITION: AZ = 0.2800 (MICROMETER SETTING), EL=0, N=11

$P_{10} = 1089$, $\sigma = 27$
$P_{12} = 1153$, $\sigma = 48$
$P_{24} = 690$, $\sigma = 7$
$P_{26} = 872$, $\sigma = 22$

$P_{12} - P_{10} = 63$, $\sigma = 21$
$P_{12} - P_{24} = 462$, $\sigma = 41$
$.807(P_{26} - P_{24}) = 146$, $\sigma = 12$
SIGNAL = 2569, $\sigma = 169$

DATA SET # 7

BEAM POSITION: AZ = 0.2800, EL = 0, N (DATA POINTS) = 10

$P_{10} = 1112$, $\sigma = 42$
$P_{12} = 1162$, $\sigma = 49$
$P_{24} = 687$, $\sigma = 12$
$P_{26} = 925$, $\sigma = 22$

$P_{12} - P_{10} = 49$, $\sigma = 13$
$P_{12} - P_{24} = 474$, $\sigma = 37$
$.807(P_{26} - P_{24}) = 192$, $\sigma = 8$
SIGNAL = 2932, $\sigma = 165$

DATA SET #9

BEAM POSITION: AZ = 0.2700, EL = 0, N = 11

$P_{10} = 985$, $\sigma = 33$
$P_{12} = 953$, $\sigma = 34$
$P_{24} = 696$, $\sigma = 20$
$P_{26} = 770$, $\sigma = 24$

$P_{12} - P_{10} = -32$, $\sigma = 8$
$P_{12} - P_{24} = 257$, $\sigma = 19$
$.807(P_{26} - P_{24}) = 59$, $\sigma = 7$
SIGNAL = 1559, $\sigma = 418$

# TABLE 4 CONTINUED

DATA SET # 10

BEAM POSITION: AZ = 0.2820, EL = 0, N = 5

$P_{10} = 1050$, $\sigma = 19$

$P_{12} = 1110$, $\sigma = 18$

$P_{24} = 682$, $\sigma = 12$

$P_{26} = 853$, $\sigma = 13$

$P_{12} - P_{10} = 59$, $\sigma = 3$

$P_{12} - P_{24} = 422$, $\sigma = 8$

$.807(P_{26} - P_{24}) = 120$, $\sigma = 2$

SIGNAL = 2173, $\sigma = 429$

DATA SET # 12

BEAM POSITION: AZ = 0.2800, EL = −4, N = 54

$P_{10} = 1067$, $\sigma = 28$

$P_{12} = 1115$, $\sigma = 21$

$P_{24} = 689$, $\sigma = 6$

$P_{26} = 938$, $\sigma = 21$

$P_{12} - P_{10} = 48$, $\sigma = 14$

$P_{12} - P_{24} = 426$, $\sigma = 18$

$.807(P_{26} - P_{24}) = 202$, $\sigma = 12$

SIGNAL = 1719, $\sigma = 97$

DATA SET # 14

BEAM POSITION: AZ = 0.2800, EL = +4, N = 63

$P_{10} = 981$, $\sigma = 31$

$P_{12} = 1062$, $\sigma = 32$

$P_{24} = 689$, $\sigma = 11$

$P_{26} = 789$, $\sigma = 19$

$P_{12} - P_{10} = 81$, $\sigma = 8$

$P_{12} - P_{24} = 373$, $\sigma = 23$

$.807(P_{26} - P_{24}) = 80$, $\sigma = 11$

SIGNAL = 1629, $\sigma = 162$

DATA SET # 15

BEAM POSITION: AZ = 0.2791, EL = 0, N = 50

$P_{10} = 1083$, $\sigma = 11.2$

$P_{12} = 1117$, $\sigma = 8.4$

$P_{24} = 692$, $\sigma = 2.1$

$P_{26} = 954$, $\sigma = 5.5$

$P_{12} - P_{10} = 34$, $\sigma = 11.4$

$P_{12} - P_{24} = 425$, $\sigma = 9$

$.807(P_{26} - P_{24}) = 211$, $\sigma = 5.1$

SIGNAL = 2511, $\sigma = 114$

# TABLE 5

## BOOTSTRAP LOADER

| LOAD ADDR | DEPOSIT |
|---|---|
| 037744 | 016701 |
| 037746 | 000026 |
| 037750 | 012702 |
| 037752 | 000352 |
| 037754 | 005211 |
| 037756 | 105711 |
| 037760 | 100376 |
| 037762 | 116162 |
| 037764 | 000002 |
| 037766 | 037400 |
| 037770 | 005267 |
| 037772 | 177756 |
| 037774 | 000765 |
| 037776 | 177560 |

# TABLE 6

## TERMINAL OUTPUT LISTING

| OZONE WT1-4 | OZONE WT1-2 | OZONE WT3-4 | GAS-2 | T1 | T2 | T3 | T4 | SIGNAL LEVEL |
|---|---|---|---|---|---|---|---|---|
| -0323 | 0013 | -0237 | -0108 | 2445 | 2459 | 2567 | 2151 | 1660 |
| -0388 | 0036 | -0424 | -0027 | 2041 | 2077 | 2104 | 1579 | 2198 |
| -0365 | 0022 | -0388 | 0010 | 1767 | 1790 | 1779 | 1299 | 2975 |
| -0447 | 0035 | -0483 | 0092 | 1773 | 1809 | 1716 | 1119 | 4095 |
| -0537 | 0036 | -0573 | 0156 | 1794 | 1831 | 1675 | 0966 | 4095 |
| -0608 | 0040 | -0649 | 0203 | 1805 | 1846 | 1643 | 0840 | 4095 |
| -0622 | 0048 | -0670 | 0237 | 1811 | 1860 | 1622 | 0793 | 4037 |
| -0586 | 0026 | -0666 | 0263 | 1797 | 1858 | 1595 | 0771 | 3715 |
| -0579 | 0081 | -0661 | 0295 | 1772 | 1853 | 1558 | 0741 | 3291 |
| -0535 | 0129 | -0665 | 0296 | 1708 | 1837 | 1541 | 0718 | 4095 |
| -0571 | 0117 | -0688 | 0303 | 1743 | 1860 | 1557 | 0706 | 3973 |
| -0580 | 0111 | -0692 | 0309 | 1756 | 1868 | 1558 | 0723 | 3045 |

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# TABLE 7
## $R_n$: DEFINITIONS

$$R_1 = -1000\left[\ln\left(\frac{I_2}{I_{02}}\right) - \ln\left(\frac{I_1}{I_{01}}\right)\right] + .807\left[\ln\left(\frac{I_4}{I_{04}}\right) - \ln\left(\frac{I_3}{I_{03}}\right)\right]$$

$$R_2 = -1000\left[\ln\left(\frac{I_2}{I_{02}}\right) - \ln\left(\frac{I_1}{I_{01}}\right)\right]$$

$$R_3 = -1000\left[.807\right]\left[\ln\left(\frac{I_4}{I_{04}}\right) - \ln\left(\frac{I_3}{I_{03}}\right)\right]$$

$$R_4 = -1000\left[\ln\left(\frac{I_2}{I_{02}}\right) - \ln\left(\frac{I_3}{I_{03}}\right)\right]$$

$$R_5 = -1000\left[\ln\left(\frac{I_1}{I_{01}}\right)\right]$$

$$R_6 = -1000\left[\ln\left(\frac{I_2}{I_{02}}\right)\right]$$

$$R_7 = -1000\left[\ln\left(\frac{I_3}{I_{03}}\right)\right]$$

$$R_8 = -1000\left[\ln\left(\frac{I_4}{I_{04}}\right)\right]$$

## APPENDIX A

## CAVITY OPTICS ALIGNMENT

In the following alignment procedure, the optics are referred to as labeled in Fig. 18. It is assumed that nothing is aligned correctly at the beginning.

1. Helium-Neon beam insertion

The first step is to inject the He-Ne tracer beam into the cavity. Using the He-Ne steering optics and the adjustments on the "insertion" mirror, the He-Ne beam should be directed through the center of the output mirror $M_1$, to the center of the vertex mirror $M_2$ and finally to the center of mirror $M_3$. This initial alignment should also force the beam through the centers of the brewster angle windows ($B_1$ and $B_2$). It is critically important that the beam passes through the center of $M_1$.

2. Alignment of Output Mirror

The He-Ne beam will have front and rear surface reflections from the output mirror which are visible on the lower beam steering mirror ($M_{18}$). Adjustment of the output mirror mount should force the two reflections to overlap the primary (incoming) spot on $M_{18}$. It may be necessary to readjust the beam steering mirrors slightly.

3. Rough adjustment of frequency selecting optics

Mirror $M_3$ should be adjusted to direct the He-Ne beam to the center of $M_4$; then mirror $M_4$ should be adjusted to direct the beam to the approximate center of the diffraction grating. The grating is blazed at 8.6 $\mu$m so the 13th and the 14th order diffracted beams will be the brightest. When the grating is tilted forward at an approximate $40^{\circ}$ angle with respect to the horizontal, the two brightest (13th and 14th) orders should be visible on $M_4$. The next highest order, 15, is somewhat fainter, but is roughly coincident with the 9.4 $\mu$m band P-12 laser line. This order, 15, is used to align the remaining optics. The grating must now be adjusted so that the 15th order first strikes $M_4$ and $M_5$ on its center line approximately half-way between the center and bottom. The small aluminum mask at the front of the chopper motor stand should be removed and the chopper wheel rotated so that the beam passes through the P-12 slot (2nd largest radius). (Fig. 21). Mirror $M_5$ can now be adjusted to direct the 15th order He-Ne beam through the chopper to the cavity end mirror $M_6$. This mirror can then be adjusted to overlap the return on $M_5$ and $M_4$. The cavity should now be roughly aligned to lase on the $CO_2$ 9.4 $\mu$m band P-12 or P-14 line.

4. Fine tuning of laser cavity

The laser should now be turned on for final adjustments. The optimum parameters are 20 Torr laser mixture at 10 mA and 23 KV, and cooling water temperature of $5^{\circ}$ to $10^{\circ}$ Centigrade. An ultraviolet light and phosphor plate can be used to detect the infrared beam at the He-Ne laser steering mirrors with insertion mirror, $M_{17}$, in place. Typically, small adjustments of $M_6$ and $M_5$ are necessary to achieve lasing on either P-14 or P-12. At this point, other lines may or may not lase through the various chopper slots. The lasing line is identified with a spectrometer set to receive the $CO_2$ laser output.

The aluminum mask should now be re-installed so that the 15th order He-Ne beam passes through the 2nd from the bottom aperture. The mask should be fine adjusted to allow lasing of the P-12 line with the chopper wheel in the appropriate position (Fig. 21). A check should be made at this point to assure that the P-12 line is actually lasing through the proper aperture in the mask. Manual rotation of the chopper wheel should now allow lasing of P-10, P-12, P-24 and P-26 through their respective slots (Fig. 21). If this is not the case, there is usually only a slight alignment error.

The first step in the trouble-shooting procedure is to determine which, if any, lines are lasing through each mask hole chopper wheel combination. If the P-12 line is the only line that lases, then the grating is not dispersing light vertically and needs to be slightly rotated in its mount. This adjustment is done while observing the He-Ne tracer beam. Now, some line should be lasing through each slot. Sometimes a small adjustment with the grating vertical control can force the proper line through each chopper slot. If this is not possible, then the total distance between $M_6$ and the grating is wrong. The distance can be increased and the dispersion increased by adjusting the He-Ne beam to lie lower on the grating. Raising the beam on the grating has the opposite effect. Repositioning requires re-tuning $M_3$, $M_4$, grating, $M_5$ and $M_6$. P-12 is the reference and should always lase through the proper aperture and channel. Then if P-26 lases through the P-24 slot, the tracer must be moved down on the grating, or if P-22 and P-24 lase through the P-24 and P-26 slots respectively, the tracer must move up on the grating. After any adjustments, P-12 must always be checked first. Before every line lases through the proper aperture, several iterations of the final alignment procedure are usually required.

## APPENDIX B

## OUTPUT/RECEIVING OPTICS ALIGNMENT

In the following alignment procedure all optics are referred to as labeled in Figure 19. It is assumed that the telescope and periscope are bolted in place.

1. Insertion of the He-Ne tracer beam.

Assuming that the tracer beam has been previously aligned in the cavity alignment mode, no adjustments should be made to the beam steering mirrors $M_{18}$ and $M_{19}$, nor to the the insertion mirror $M_{17}$. The tracer beam can be transferred to the external alignment mode by adjusting the translation stage Y control. Note that the alignment tracer beam from $M_{17}$ to $M_7$ must be an extension of the line defined by the tracer beam between $M_2$ and $M_{17}$ in the cavity mode. The requirement is to position Y so that this is true. The suggested procedure is to withdraw the insertion mirror and mark the center of the $CO_2$ laser beam on $M_7$ by burning a small spot on a piece of paper directly in front of $M_7$. The insertion mirror is replaced and the Y control is adjusted so that the tracer beam strikes $M_7$ at the point indicated by the $CO_2$ laser beam.

After the tracer beam has been adjusted, two cardboard masks with 2mm diameter holes should be centered on lenses $L_1$ and $L_2$. The beam should be directed through both masks by the adjustment of $M_7$ and $M_8$. The beam is now properly inserted.

2. Alignment of Telescope Optics

The beam splitter is antireflection coated on one side which must face toward $L_2$. The brighter of the two diverging reflections from the beam splitter should be adjusted to be incident on the center of telescope mirror $M_{11}$. It may be necessary to insert a shim between the beam splitter and mount to achieve this. $M_{11}$ then is adjusted to steer the beam halfway between the center and the top of the secondary mirror $M_{12}$ which directs the mildly diverging beam to the approximate center of the off-axis parabolic mirror $M_{13}$. It may be necessary to readjust the beam splitter, $M_{11}$, and $M_{12}$, to center the beam on $M_{13}$. The beam should be close to centered on $M_{14}$ and $M_{15}$. If this is not the case, $M_{13}$ will have to be adjusted by placing crosshairs at the opening to the periscope in front of $M_{14}$ and the exit to the periscope in front of $M_{15}$. If the beam is adjusted with $M_{13}$ so that the center passes through the center line defined by the crosshairs there will be no aperturing by the periscope. For the alignment of the spotting telescope see Section 6.

It should be noted that the function of $L_1$ and $L_2$ is to expand the laser beam by a factor of two such that the expanded beam just fills the beam splitter and the final telescope mirrors $M_{13}$, $M_{14}$, and $M_{15}$. The beam will come to a focus at F one-third of the distance between $L_1$ and $L_2$. A spatial filter can be placed at this point.

3. Alignment of Detection Optics

To align the reference beam, only $M_9$ needs to be adjusted for the beam to be centered on detector $D_1$. A flat mirror should then be temporarily inserted in front of $M_{14}$ and adjusted to fold the beam back upon itself through the beam splitter to $M_{10}$,

which then directs the beam to detector $D_2$.

The insertion mirror $M_{17}$ can now be removed by adjusting the translation stage X control and the laser turned on. Mirrors $M_7$ and $M_8$ can now be fine adjusted to force the infrared beam through the mask holes centered on lenses $L_1$ and $L_2$. The $CO_2$ beam is now co-axial with the tracer beam. Mirror $M_{17}$ can now be re-inserted and the temporary flat mirror removed to allow retro-reflector targeting with the He-Ne beam. Fine adjustments with the telescope primary mirror, $M_{13}$, will probably be necessary later to maximize the infrared return because the visible beam may not be exactly concentric with the $CO_2$ beam. A small spotting scope and a flat mirror can now be aligned near $M_{14}$ for visual targeting which partially blocks $M_{14}$. (See Section 6.) However, the He-Ne beam is still inserted by $M_{17}$ and the retro-reflector return can be observed through the spotting telescope.

The cardboard masks should now be removed from $L_1$ and $L_2$. The final adjustment is made by focusing the telescope using the micrometer control on $M_{12}$. This adjustment is done while observing the signal oscilloscope.

## APPENDIX C

## DATA ACQUISITION

In the following, it is assumed that the PDP-11/05 computer is powered down. The General Electric Final Report[3] may be used as a reference.

1. Bootstrap and Absolute Loader

First the computer key must be turned to AC and the Teletype to REMOTE; then the numbers listed in Table 5 must be loaded into the appropriate addresses via the PDP-11 front panel switches.

Next, a paper tape labeled "Absolute Loader" must be inputed via the paper tape reader/teletype terminal.

The tape loading procedure is as follows:

a) PDP-11/05 -- Halt
b) Load tape into sprocket on teletype (Teletype on FREE)
c) Advance tape up to the first program holes, then put Teletype on STOP
d) PDP-11/05 -- Load Address 037744

Via computer front panel switches,

ENABLE
START

e) Teletype to START

when the tape stops loading, turn the teletype to STOP and the computer to HALT.

2. Program and Parameter Loading

Now a number of paper tapes must be loaded in the following order. (The loading procedure is identical to that for the "ABSOLUTE LOADER" except for the starting Address).

1. Main program tape XSTR -- Start Address 037500
2. Subroutine tape XSYST -- Start Address 037500
3. Channel Assignment tape -- Start Address 007000
4. Parameter Tape -- Start Address 012000

NOTE: Program XSETR will stop near the middle and XSYST will stop 8 times during loading. They are a collection of small programs. After each such stop proceed as follows:

PDP 11/05 HALT
LOAD ADDRESS 037500
ENABLE
START

This concludes the actual loading procedure.

3. Running the Program -- Data acquisition

The interface unit which also controls the chopper wheel motor should be turned on

and the outputs of the detectors monitored on an oscilloscope. The chopper should be set to 35 to 40 hz by adjusting the control knob on the front of the interface. The detector gains should be set, using the gain switches on the interface front panel, so that the reference signal is not clipped. Normally a screen is placed between the beam splitter and the reference detector as an attenuator and the amplifier set at its lowest gain, position 1. The analytic signal detector gain should be set so that this signal is less than 1/2 the amplitude of the reference signal. This will usually occur when the amplifier gain setting is in either position 2 or position 3, depending on the retro-reflector distance.

The teletype power switch is set to REMOTE and the computer to HALT. To begin data acquisition proceed as follows:

PDP 11/05 Load Address 013000
ENABLE
START

The teletype will respond with the format listed in Table 6. Columns 1 to 8 are weighted optical transmissions and column 9 is a relative return signal at the amplifier output beyond the signal attenuator. The value should normally be between 1000 and 4000. If this is not the case, the amplifier attenuator setting should be changed. For the present parameter tape, the numbers $R_n$ in columns 1-8 are defined in Table 7. Where $I_{ON}$ is the reference strength of the outgoing Nth frequency, $I_N$ is the return strength of the Nth frequency and N = 1,2,3,4 refers to the laser lines of the $CO_2$ 9.4 μm band of $P_{10}$, $P_{12}$, $P_{24}$, and $P_{26}$ respectively. Note that the automatic gain control circuit will adjust the system gain so that the laser line with the minimum absorption will have a ratio $I_N/I_{NO} = 1/2$. Therefore, one of the $R_n$ values should nominally equal 693.